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Feasible Trajectory Generation for Atmospheric Entry Guidance

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An atmospheric entry trajectory planner is developed that generates a feasible trajectory and associated bank angle profile. Feasibility denotes that the initial and final state conditions, the path and control constraints, and the nominal equations of motion are all satisfied. Feasible trajectories are easier to track, and thus enhanced performance is expected when the trajectory planner is combined with a tracking law for entry guidance. Insights from computing maximum crossrange trajectories are factored into the design of the planner, and as a result that it can generate trajectories to most of the landing footprint. Drag profile design is central in the planning approach, but in addition both longitudinal and lateral motions are accounted for, including bank reversal planning, and the assumption of zero flight path angle is not required. Comparisons of trajectories created by the new planner and optimal trajectories and guidance simulation results using an algorithm based on the new planner demonstrate the performance improvements.

Nomenclature

A_{max}	=	maximum allowable normal acceleration, ft/s^2
C_γ	=	Coriolis acceleration term in γ' equation, rad$\cdot$ s^2/ft^2
C_ψ	=	Coriolis acceleration term in ψ' equation, rad$\cdot$ s^2/ft^2
C_D	=	coefficient of drag
C_L	=	coefficient of lift
D	=	drag acceleration, ft/s^2
$D_{e.g.}$	=	equilibrium glide drag boundary, ft/s^2
D_{max}	=	vehicle constraint upper drag boundary, ft/s^2

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D_{maxf}	=	feasible upper drag boundary, ft/s^2
D_{minf}	=	feasible lower drag boundary, ft/s^2
D_{ref}	=	reference drag profile, ft/s^2
E	=	energy divided by vehicle mass, ft^2/s^2
$\tilde{E}$	=	normalized energy
$\tilde{E}_m$	=	drag interpolation shaping parameter
g	=	gravitational acceleration, ft/s^2
h	=	altitude, ft
h_s	=	scale height, ft
k_1	=	integral gain in drag tracking law
k_2	=	proportional gain in heading angle tracking law
k_3	=	integral gain in heading angle tracking law
L	=	lift acceleration, ft/s^2
L_n	=	normal acceleration, ft/s^2
M	=	Mach number
m	=	vehicle mass, slugs
P_1	=	normalized downrange parameter
P_2	=	normalized crossrange parameter
$\bar{q}$	=	dynamic pressure, lbf/ft^2
Q	=	heat load, BTU/ft^2
$\dot{Q}$	=	thermal flux, BTU/ft^2/sec
r	=	radial distance from vehicle to planet center, ft
r_{eq}	=	planet surface radius at equator, ft
S	=	reference wing area, ft^2
t	=	time, s
V	=	planet-relative speed, ft/s
α	=	angle of attack, rad
γ	=	flight path angle, rad
μ	=	gravitational constant, ft^3/s^2
ω_n	=	natural frequency of desired drag error dynamics, rad/s
ω_p	=	angular rate of planet rotation, rad/s
ϕ	=	latitude, rad
ψ	=	heading angle with $\psi = 0$ as due east, rad

ψ_{ref} = reference heading angle profile, rad

ρ = atmospheric density, slugs/ft^3

ρ_{eq} = atmospheric density at r_{eq}, slugs/ft^3

σ = bank angle, rad

θ = longitude, rad

ζ = damping ratio of desired drag error dynamics

$3-DOF$ = three-degrees-of-freedom

AGC = Advanced Guidance and Control

FBL = feedback linearization

HAC = Heading Alignment Cone

PD = position and derivative feedback control

$TAEM$ = Terminal Area Energy Management

Introduction

To reduce cost and increase safety, a goal for next generation reusable launch vehicles (RLVs) is aircraft-like operation. To realize this goal requires advances in entry guidance.[1] An entry guidance algorithm determines, repetitively during entry, the bank angle profile, and if appropriate also the angle of attack profile, required to steer the vehicle to the desired landing site. In the context of the entry guidance problem, one or both of these angles are considered to be the controls. The equations of motion relating the control profiles to the vehicle position and velocity are nonlinear and must be based on vehicle and atmospheric models that are inaccurate. The position and velocity inputs to the guidance algorithm will also be inaccurate. The guidance problem that the algorithm solves is further complicated by the need to respect path constraints on vehicle heating, acceleration and dynamic pressure, and control constraints on the bank angle and angle of attack. Most guidance algorithms operate with a reference trajectory. Although for vehicles with a limited flight envelope and focused mission it is adequate to have the trajectory generator on the ground, on-board trajectory generation is arguably a requirement for RLVs to achieve aircraft-like operation for the entire set of nominal and abort mission scenarios.

The state-of-the-art operational entry guidance is embodied in the entry guidance algorithm for the U.S. Space Shuttle Orbiter.[2] The algorithm is comprised of a trajectory planning function and a trajectory tracking function. Much of the complexity and uncertainty of the entry trajectory planning problem is circumvented by using the drag acceleration as a surrogate control variable. The path constraints and final altitude constraint are converted to drag constraints. Assuming flight on a great circle arc to the target longitude and latitude to determine the required range, a drag profile satisfying the constraints and producing the required range is planned. With energy as the independent variable, determining range for a drag profile requires the integration of a scalar first-order differential equation. This differential equation under the given assumptions is an exact kinematic relation between drag and the derivative of range with respect to energy. A drag tracking law specifies the magnitude of the bank angle. The sign of the bank angle is determined by a heading error corridor. In the Shuttle entry guidance only the longitudinal motion is considered in the planning. Various authors[3–7] have proposed and evaluated potential improvements to the Shuttle entry guidance; in each case the planning is limited to the longitudinal motion.

To achieve aircraft-like operation and the capability of "returning the vehicle safely in any situation where this is physically possible,"[1] future RLVs will need to fly trajectories that differ significantly from great circle arcs and have a guidance algorithm that can plan and execute such trajectories. The Shuttle trajectory planning strategy has been extended[8,9] to combined longitudinal and lateral motion planning. By making two mild approximations,[8] the planning requires the integration of only three first-order differential equations. The altitude and flight path angle dynamics are eliminated, which, in addition to order reduction, avoids the sensitivity in planning due to phugoid-like motion. The complexity of the planning problem is further reduced by breaking the problem into two subproblems and using a successive approximation approach. The longitudinal subproblem is essentially the drag planning problem solved in the Shuttle guidance, except that the great circle arc assumption has been eliminated. By solving the lateral subproblem, bank reversals are planned and the curved path to the target is computed. Accounting for the curvature allows the drag profile to be planned more accurately, which is especially important for high-crossrange targets. The planner was combined with a tracking law to construct an entry guidance algorithm referred to as Evolved Acceleration Guidance Logic for Entry (EAGLE).[9] The trajectory planner is fast enough that trajectory re-planning to correct for the effects of tracking errors can be part of the real-time guidance strategy. EAGLE can deliver an entry vehicle to the start of a terminal area energy management (TAEM) phase, as does the Shuttle guidance, or it can deliver to a parachute deploy point. Extensive simulation testing results for EAGLE are presented in Saraf et al.[9] EAGLE performed extremely well in an independently conducted evaluation[10] of several entry guidance algorithms.

In this paper we present a new trajectory planner that possesses near-maximum downrange and crossrange capabilities and that addresses certain limitations of the previous EAGLE planner. 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. In the EAGLE testing mentioned above, despite the overall excellent performance, tracking difficulties were observed in some suborbital abort cases. The entry guidance of low L/D capsules, such as those used for Mars landing, presents a more serious 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.[6] A different approach to constructing a more easily tracked drag profile is presented in this paper. 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. Pre-tracking has been used previously by Mease et al.[8] and Lu and Shen.[11,12] 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. In addition, the new planner is not based on the assumption of a small flight path angle.

The purpose of this paper is to present the new entry trajectory planning approach and demonstrate the beneficial features of this approach. The performance of the new planner is demonstrated both separately and as the planning function in EAGLE, replacing the original planner. Testing and validation under a broad range of conditions is outside the scope of this paper. Other approaches to entry guidance can be found in the papers[11–19] and the references therein.

Entry Guidance Problem Formulation

The entry guidance problem considered here is to determine for a given initial state the α and σ commands throughout the entry such that the vehicle path constraints, control constraints, and the final conditions are satisfied. This section describes the formulation and supporting models. Because the focus of this paper is trajectory planning, we do not explicitly address modeling or navigation uncertainties, except briefly in the Results section. EAGLE has been shown to adequately accommodate these important aspects of the guidance problem in other work.[8–10]

Entry Dynamics

The translational dynamics of an atmospheric entry vehicle are defined with respect to a planet-fixed coordinate frame and with energy E as the independent variable. $E = V^2/2 - \mu/r$, where V is the planet-relative velocity of the vehicle, r is the radial distance from the vehicle's center of mass to the planet center, and μ is the gravitational constant. With energy as the independent variable, the vehicle's translational motion can be modeled by five differential equations. The control variables are taken to be bank angle σ

and angle of attack α. Angle of attack appears in the equations of motion through lift and drag, while bank angle appears explicitly. Neglecting winds and centripetal acceleration from planet rotation, the equations of motion, consistent with those given in Ref. 20 except for the transformation to energy as the independent variable, are

$$
\begin{aligned}
\theta' &= -\frac{\cos\gamma\cos\psi}{r\cos\phi}\left(\frac{1}{D}\right) \\
\phi' &= -\frac{\cos\gamma\sin\psi}{r}\left(\frac{1}{D}\right) \\
r' &= -\sin\gamma\left(\frac{1}{D}\right) \\
\psi' &= \frac{\cos\psi\tan\phi\cos\gamma}{r}\left(\frac{1}{D}\right) + \frac{1}{V^2\cos\gamma}\left(\frac{L\sin\sigma}{D}\right) + \mathcal{C}_\psi \\
\gamma' &= \left(g - \frac{V^2}{r}\right)\frac{\cos\gamma}{V^2}\left(\frac{1}{D}\right) - \frac{1}{V^2}\left(\frac{L}{D}\cos\sigma\right) + \mathcal{C}_\gamma
\end{aligned}
\tag{1}
$$

where θ is the longitude, ϕ is the declination latitude, ψ is the heading angle with $\psi = 0$ as due east, and γ is the flight path angle. Both γ and ψ describe the orientation of the planet-relative velocity vector. The bank angle σ is defined such that a bank to the right is positive and zero bank corresponds to the lift vector directed upward in the longitudinal plane. Initial control and state variable values will be denoted with subscript "0", while target state values will be denoted with subscript "f". The lift L and drag D accelerations are given by

$$
\begin{aligned}
L &= \frac{1}{2}\rho(r)V^2 \cdot \frac{S}{m} \cdot C_L(\alpha, M) \\
D &= \frac{1}{2}\rho(r)V^2 \cdot \frac{S}{m} \cdot C_D(\alpha, M)
\end{aligned}
\tag{2}
$$

where $\rho(r)$ is the density as a function of altitude, $C_L(\alpha, M)$ and $C_D(\alpha, M)$ are the lift and drag coefficients as functions of angle of attack α and Mach number M, S is the reference area, and m is the vehicle mass. Specific gravity is modeled as $g = \mu/r^2$. The density variation with altitude is modeled using the exponential equation

$$\rho(r) = \rho_{eq} e^{-\frac{(r - r_{eq})}{h_s}} \tag{3}$$

where r_{eq} is the equatorial radius of the planet, and h_s (called scale height) and ρ_{eq} are constants. The terms $\mathcal{C}_\psi$ and $\mathcal{C}_\gamma$ are the Coriolis accelerations due to planet rotation and are given as

$$
\begin{aligned}
\mathcal{C}_\psi &= -\left(\frac{2\omega_p}{VD}\right)(\tan\gamma\sin\psi\cos\phi - \sin\phi) \\
\mathcal{C}_\gamma &= -\left(\frac{2\omega_p}{VD}\right)\cos\psi\cos\phi
\end{aligned}
\tag{4}
$$

where ω_p is the angular rate of planet rotation.

Path and Control Constraints

The vehicle has upper limits on dynamic pressure, aerodynamic acceleration, and heat flux. The limit on dynamic pressure is given by

$$\overline{q} = \frac{1}{2}\rho V^2 \leq \overline{q}_{max} \tag{5}$$

The constraint on aerodynamic acceleration is expressed as

$$L_z = L\cos\alpha + D\sin\alpha \leq A_{max} \tag{6}$$

Vehicle thermal constraints are treated by using stagnation point heat flux as the sole indicator. The heat flux is constrained according to the heating model

$$\dot{Q} = c\rho^{1/2}V^{3.15} \leq \dot{Q}_{max} \tag{7}$$

where c is a vehicle-dependent constant.

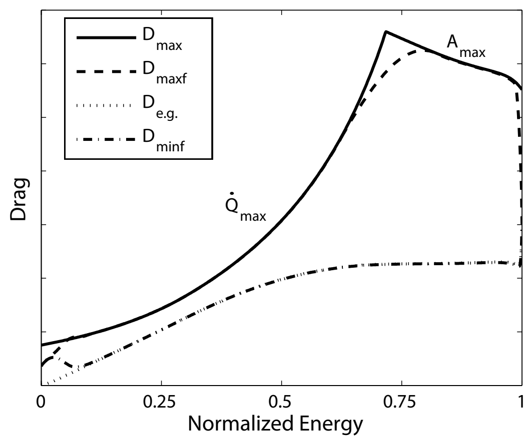


Figure 1. Drag boundaries

For drag acceleration guidance methods, the vehicle constraints are converted to an upper drag boundary using the following procedure. First the constraints are converted to separate drag constraints. The dynamic pressure, normal acceleration and heat flux constraints take the forms

$$D \leq \overline{q}_{\max}\frac{S}{m}C_D \tag{8}$$

$$D \leq \frac{A_{\max}}{\sin\alpha + \frac{L}{D}\cos\alpha} \tag{9}$$

$$D \leq \frac{1}{2}\left(\frac{\dot{Q}_{\max}}{cV^{3.15}}\right)^2 V^2 \frac{S}{m} C_D \tag{10}$$

Three drag boundary curves are defined by separately treating Eqs. (8-10) as equalities. A composite maximum drag profile, referred to as D_{max}, is constructed by taking the minimum of the three drag boundary values at each energy value. An example of a D_{max} profile is shown in Fig. 1. The vehicle constraints are met when $D \leq D_{max}$. The maximum and minimum drag boundaries depend on α. In our approach, the drag profile planning is always performed for a fixed α-profile. If the α-profile is treated as adjustable in the planning process, then the planning is conducted in a hierarchical manner in which the α-profile is adjusted iteratively outside the drag planning, while in each cycle the drag is planned with a fixed α-profile. If α is commanded for tracking, it is not allowed to differ by more than a few degrees from the profile used for planning.

A lower boundary is also constructed in the D versus E plane, though it is based on vehicle performance capabilities instead of safety-related constraints. The boundary, which we denote $D_{e.g.}$, is constructed from the zero-bank equilibrium glide condition, which occurs when $\gamma' = 0$ and $\sigma = 0$. A vehicle flying in this condition has just enough lift to maintain its flight path angle. The vehicle cannot maintain steady flight with $D < D_{e.g.}$. However, flying with $D < D_{e.g.}$ does not necessarily pose a risk to the vehicle. For this reason the boundary is considered a soft boundary, i.e., one that does need not to be enforced strictly. Figure 1 shows an example of a $D_{e.g.}$ profile.

Limits are placed on the magnitudes of the first and second time derivatives of the σ and α guidance commands according to

$$\begin{aligned} &|\dot{\sigma}| \leq \dot{\sigma}_{max}, \quad |\ddot{\sigma}| \leq \ddot{\sigma}_{max} \\ &|\dot{\alpha}| \leq \dot{\alpha}_{max}, \quad |\ddot{\alpha}| \leq \ddot{\alpha}_{max} \end{aligned} \tag{11}$$

Equation 11 does not necessarily represent vehicle limits. In trajectory planning, more conservative bounds may be used to save capability for tracking.

Target Conditions

The target conditions are application-specific. For example, the Space Shuttle ends its entry phase by starting a Terminal Area Energy Management (TAEM) phase, which prepares it for a runway landing. For the computations described in this paper, we adopt the target TAEM initiation point conditions as defined for the Advanced Guidance and Control (AGC) study.[10] Under the conventions of that study, entry terminates at a specified final speed, V_f. The final altitude h_f is specified with a tolerance of $\pm$3000 ft, the final horizontal distance to the Heading Alignment Cone (HAC) point should be greater than or equal to 27 n miles and less than or equal to 33 n miles, and the final heading angle should be within 5 deg of the line of sight to the HAC point. EAGLE can also be configured for a parachute deployment target. EAGLE handles both cases by targeting a specific point in position space. In the case of targeting for TAEM, the TAEM point, represented as (h_f, θ_f, ϕ_f), is targeted. In order to meet the final heading requirement, EAGLE changes the location of the TAEM point on the TAEM circle each time it updates the reference trajectory (see Ref. 9). In the case of targeting for parachute deployment conditions, (h_f, θ_f, ϕ_f) is taken as the desired chute deployment point and V_f becomes the chute deployment speed. In both cases, the final altitude h_f is enforced by specifying a final drag value. The accuracy of this method of enforcing h_f depends on the accuracy of the models for density and coefficient of drag.

Entry Guidance Strategy

The objective of an entry guidance algorithm is to solve the entry guidance problem to sufficient accuracy for the set of expected initial and final conditions, despite modeling and navigation errors and delay and inaccuracy in the execution of the guidance commands. We assume that a solution to the guidance problem exists. The task of selecting a feasible entry target (landing site) is not addressed here. In this section we describe the basic features of the guidance strategy employed in EAGLE. EAGLE is composed of a trajectory planner and a trajectory tracker. The trajectory planner features discussed in this section are common to the old and new planner. In the subsequent section, the improved features of the new planner are described and the planning algorithm is given.

Trajectory Planning

EAGLE plans a full 3-DOF trajectory by designing a drag profile and scheduling the bank reversal(s). For the purposes of this paper, we assume that the α-profile is given and not to be modified by the planner. (Other work[21,22] by the authors has examined onboard α-profile selection for increased ranging capability. Even if alpha profile selection is part of the planning process, the discussion given here would still apply, due to the hierarchical manner in which the α-profile is adjusted iteratively outside the drag planning.) The first objective in the drag planning is to achieve the downrange of the target. Other constraints, namely the initial and final altitudes and the vehicle constraints, are also enforced during the drag design process. The new planner enforces more constraints, such as limits on $\dot{\sigma}$ and $\ddot{\sigma}$, as described in the next section. The objective of the bank sign planning is to achieve the crossrange of the target.

For drag planning, the planner creates a family of constraint-observing drag profiles that differ by the value of one parameter, P_1. The drag planning entails selecting a value for P_1 that achieves the downrange distance consistent with the target conditions. The parameter associated with the bank sign planning is referred to as P_2. P_2 is the normalized energy at which the primary bank reversal begins. The initial bank sign is chosen to turn the vehicle toward the target. Though other bank reversals may be specified at fixed normalized energy values, they are left fixed and not adjusted by the planner. The selection of P_2 determines the final crossrange, since it is the only free parameter associated with the bank sign profile.

Trajectory Tracking

The purpose of the trajectory tracking function is to command σ and α such that the vehicle follows the reference trajectory produced by the planner. The tracking function accomplishes this by tracking drag, tracking heading angle (though only late in entry), and executing timed bank reversals. Bank angle is treated as the primary control variable. Because the tracking law is also used in the new planning process, we describe it briefly here. For more a complete discussion than is given here, including a description of how limited α commands are issued to control high-frequency drag error in a secondary tracking law, please see Ref. 9.

Both the drag tracking law and the heading angle tracking law are based on feedback linearization. The drag tracking law is designed to achieve second-order linear drag error dynamics of the form

$$(D'' - D''_{ref}) + 2\zeta\omega_n(D' - D'_{ref}) + \omega_n^2(D - D_{ref}) + k_1 \int (D - D_{ref})dE \quad = \quad 0 \tag{12}$$

where ζ is a constant to be tuned, ω_n is scheduled with dynamic pressure, k_1 is a constant gain, and

$$D'' \quad = \quad a + b(L/D)cos\ \sigma \tag{13}$$

Variables a and b are functions of the state variables and α that have been given elsewhere.[9] Equation (13) is substituted into Eq. (12), and Eq. (12) is solved for σ at each guidance cycle during entry.

Similarly, the heading tracking law is designed to achieve first-order linear heading angle error dynamics of the form

$$(\psi' - \psi'_{ref}) + k_2(\psi - \psi_{ref}) + k_3 \int (\psi - \psi_{ref})dE \quad = \quad 0 \tag{14}$$

where k_2 is scheduled with dynamic pressure and k_3 is a constant gain. The equation for ψ' (see Eq. (1)), which contains σ, is substituted into Eq. (14), and Eq. (14) is solved for σ at each guidance cycle during entry.

The bank angle command is taken as a weighted combination of the σ values obtained from the two tracking laws. Up until the last part of entry, all of the control weighting is assigned to the drag tracking law. Drag tracking is used exclusively at first because it is challenging and requires full attention. In the absence of modeling error, perfect drag tracking will also result in the reference heading angle being followed perfectly. In actuality, tracking drag exclusively will result in an off-nominal bank command history, causing heading angle to stray from the nominal as well. Planning updates correct the effects of heading error by resetting the timing of the primary bank reversal and starting the reference trajectory from the current heading angle. After the last reversal has been executed, planning updates cannot correct heading error in this manner. For this reason, heading tracking is mixed in at roughly even proportion with drag tracking after the last bank reversal is completed.

New Trajectory Planner

Objectives

The first goal for the new trajectory planner is to be able to plan trajectories that are within the capability of the vehicle to fly, i.e., to plan feasible trajectories. A feasible trajectory is one that meets the boundary conditions and the vehicle constraints and that satisfies the equations of motion with the nominal models. The boundary conditions include matching the initial entry state, the initial bank angle σ_0, and the target conditions within certain tolerances. For feasibility as we define it here, we do not require matching the initial angle of attack α_0. Testing of an earlier version of the new planner that did match α_0 led us to conclude that the potential benefits did not justify the increased level of algorithm complexity.

The previous planner designed a three-segment piecewise-linear-in-energy drag profile. The middle segment was taken constant drag. The initial drag value was determined by the initial conditions and the final drag value was determined by the final conditions. The segment breakpoints were chosen to match the shape of the D_{max} boundary in the D versus E plane. The height of the middle segment was chosen to match a desired trajectory length. Portions of the three-segment drag profile that exceeded D_{max} were replaced by the corresponding sections of D_{max}. While this method works well over a large part of the entry corridor for orbital entry (it performed well in the AGC study[10]), some problems arise when it is used for suborbital entry. The short duration of suborbital entry makes it harder to correct for the tracking errors that result from infeasibilities in the reference trajectory. Infeasibilities associated with the previous drag design method include not matching σ_0 and γ_0, discontinuous changes in σ and γ at segment breakpoints and at breakpoints introduced by adopting sections of D_{max}, excessive bank angle derivatives, and incompatibility with the γ' equation of Eqs. (1). Arbitrary drag shapes may specify values for γ' that demand more vertical lift than the vehicle can attain by simply lowering $|\sigma|$. Some of the infeasibilities can be quite significant during orbital entry as well, particularly γ' incompatibility, and discontinuities in γ resulting from flying segments of the D_{max} boundary. The X33-type vehicle model used for the AGC testing had an L/D of about one. Tracking problems for infeasible trajectories will be more serious for lower L/D vehicles, such as capsules.

The second goal for the new trajectory planner is to be able to plan trajectories to the entire landing footprint. The challenging targets not covered by the original EAGLE planner are those near the boundary.

These targets are the endpoints of optimal trajectories, yet ideally we would like the planner to compute trajectories to these points without actually solving optimal control problems.

Optimal Trajectory Features

To characterize the features of trajectories to the boundary points of the landing footprint, optimal trajectories were generated using ASTOS[23] – an optimal control and simulation tool for aerospace applications. ASTOS solves trajectory optimization problems using collocation or direct multiple shooting. The optimization problem we solved is to maximize or minimize the final latitude for a given final longitude θ_f, subject to the initial conditions, equations of motion, constraints, and boundary conditions given earlier. Also, h was constrained to be below h_0 to exclude skip trajectories. The value for θ_f was varied to obtain vertices to construct an optimal landing footprint polygon for a particular initial condition (labeled EG16) given in the Performance Demonstration section.

The following features of the optimal trajectories were observed and are used to guide the new planner design to increase its crossrange and downrange capabilities. $D(\tilde{E})$ profiles of maximum-range trajectories lie close to the equilibrium glide drag profile, $D_{e.g.}$, which corresponds to $\gamma' = 0$ and $\sigma = 0$. An example of a $D_{e.g.}$ profile is shown in Fig. 1. $D(\tilde{E})$ profiles of minimum-range trajectories tend to closely follow the D_{max} boundary. Maximum crossrange trajectories show a reduction in drag in the last part of entry, which extends range once the vehicle is headed in the desired direction; with the drag reduction there is a corresponding decrease in the bank angle magnitude and an increase in the vertical component of lift. By imitating these behaviors, the new planner is capable of achieving near-optimal downrange and crossrange.

Feasible Drag Profiles with Optimal Features via Interpolation and Pre-Tracking

The three-segment linear drag profile design of the previous planner is replaced with an interpolation-based feasible drag design method. Drag is taken as a weighted combination of minimum and maximum drag profiles. The interpolation depends on a parameter P_1 defined such that $P_1 = 0$ produces the maximum drag profile, $P_1 = 1$ produces the minimum drag profile, and $0 < P_1 < 1$ produces a drag profile that lies between the two extremes. The use of interpolation is motivated by computation time. During the search for P_1, many drag profiles may be considered. Enforcing feasibility on each profile would increase computation time. Using the interpolation method, direct enforcement of feasibility is only required for the first two profiles that are tested, the lower and upper drag profiles. Our experience indicates that trajectories generated from drag interpolation will be feasible to sufficient accuracy, if both the lower and upper drag profiles are associated with feasible trajectories.

The desired near-optimal behavior is built into the planner in the following manner. The upper drag profile used for interpolation is taken as a feasible variant of the D_{max} boundary in the D versus E plane, and is referred to as D_{maxf}. The lower drag profile is taken as a feasible variant of $D_{e.g.}$ in the D versus E plane, and is referred to as D_{minf}. Figure 1 shows examples of D_{max}, D_{maxf}, $D_{e.g.}$, and D_{minf} profiles. The crossrange-enhancing feature is implemented at the interpolation stage of drag design, and is not applied to D_{maxf} or D_{minf}.

The procedures used for generating D_{maxf} and D_{minf} are basically the same, so only the procedure for creating D_{maxf} will be described in detail. The trajectory planner creates D_{maxf} by pre-tracking D_{max}. The term "pre-tracking" has been used to clarify the point that the tracking is a simulation performed by the planner. The planner performs a tracking simulation and takes the resulting drag history as D_{maxf}, a feasible variant of D_{max}. During the simulation, the initial conditions, equations of motion with the nominal models, and control derivative limits are all enforced to ensure that D_{maxf} is feasible. Another control constraint, $|\sigma| > \sigma_{min}$, is enforced (except during bank reversals) to ensure some lateral control authority for tracking. For the results presented in this paper $\sigma_{min} = 5$ deg. The same feedback linearization (FBL) plus proportional-derivative (PD) drag tracking law used in EAGLE's trajectory tracking function is used to pre-track D_{max}, though the gain tuning is different. For the pre-tracking, $\zeta = 1$ since an overshoot is not desired. Due to rate saturation of σ, an overshoot in drag may occur if ω_n is too high. A search is performed for the value of ω_n that achieves the closest drag tracking while maintaining the overshoot below a specified tolerance. The overshoot is defined as the maximum value of the drag error, where drag error is $D(E) - D_{max}(E)$. The tolerance is small but non-zero to allow for minor numerical error effects in the steady-state tracking response. The resulting drag profile is taken as D_{maxf}. The search for ω_n is performed by the planner during the creation of the D_{maxf} profile each time a trajectory is planned, though re-determining ω_n each time may not be necessary.

D_{max} is modified before it is pre-tracked to create D_{maxf} to smooth the slope discontinuities at energy values where a different vehicle constraint becomes active. Cubic bridging segments are applied at the corners of D_{max} to give a smooth transition from one constraint curve to the next. A final cubic segment is added to smoothly connect D_{maxf} (not D_{max}) to D_f at the end of entry. The corner cubic segments match the value and slope of D_{max} at points where they connect to it. The final segment matches the value, slope and curvature of D_{maxf} at its connection point.

The same procedure is used to create a feasible variant of $D_{e.g.}$, except that there are no corners in $D_{e.g.}$ to smooth out. The resulting minimum drag profile is labeled D_{minf}. For low-energy entry conditions or vehicles with low lift to drag ratio, it might be difficult or impossible to attain steady tracking of $D_{e.g.}$. In these cases D_{minf} is created by integrating the full equations of motion from the initial entry state with $\sigma = \sigma_{min}$. This method could always be used to generate D_{minf}, but pre-tracking $D_{e.g.}$ is the preferred method when possible because it precludes the excessive phugoiding that can result from flying with $\sigma = \sigma_{min}$.

In general it is not possible to track $D_{e.g.}$ with $\sigma = 0$. Experience has shown that tracking $D_{e.g.}$ requires non-zero σ commands and that γ decreases slowly with time while $D_{e.g.}$ is tracked. The observation that $\sigma \neq 0$ indicates that $D_{e.g.}$ is a conservative minimum drag boundary. The conservatism can be removed by multiplying C_L by $1 + \eta$ during the computation of $D_{e.g.}$, where η is a small number such as 0.05. During the computation of D_{minf}, σ will eventually saturate at σ_{min} and a small phugoid oscillation will occur. The magnitude of the phugoid oscillation decreases as η decreases. The lowest drag profile in Fig. 2c was generated using $\eta = 0.07$. $D_{e.g.}$ in Fig. 1 was generated with nominal lift ($\eta = 0$). The addition of phugoid motion in this manner increases range. This is consistent with the optimal footprint, whose maximum-range trajectories oscillate slowly near $D_{e.g.}$. While this modification is important for planning trajectories to the maximum range boundary of the footprint, it may not be required for planning within an operational guidance algorithm.

Interpolation between D_{minf} and D_{maxf} is performed according to

$$D(\tilde{E}) = D_{minf}(\tilde{E}) + \frac{1 - P_1}{1 + e^{k(\tilde{E} - \tilde{E}_m)}} \left(D_{maxf}(\tilde{E}) - D_{minf}(\tilde{E}) \right) \tag{15}$$

where P_1 is the normalized downrange parameter and $k > 0$ and $\tilde{E}_m$ are shaping parameters. Equation (15) approximates linear interpolation at values of $\tilde{E}$ sufficiently less than $\tilde{E}_m$. As $\tilde{E}$ increases, drag drops smoothly to D_{minf}. The value of k determines how quickly the transition to D_{minf} occurs. For the results presented in this paper, $k = 30$ and $\tilde{E}_m = 0.85$. Drag is reduced at the end of entry to increase crossrange, imitating this feature observed in the optimal trajectories. As it is, Eq. (15) does not produce D_{maxf} when $P_1 = 0$ because of the crossrange-enhancing drag reduction at the end. The equation can be modified to gradually eliminate the drag reduction as P_1 approaches 0. One way to do this is to replace P_1 with $max(1.2P_1 - 0.2,\ 0)$ and $\tilde{E}_m$ with $\tilde{E}_m - 2\ min(1.2P_1 - 0.2,\ 0)$ in the equation. Figure 2 gives an example of drag profiles generated using Eq. (15) with the substitutions. For low energy cases, including the suborbital cases of the AGC study,[10] the total entry time is not sufficient for the drag reduction method that has been described to be an effective means of increasing crossrange. In these cases, simple linear interpolation is applied according to

$$D(\tilde{E}) = P_1 D_{minf}(\tilde{E}) + (1 - P_1) D_{maxf}(\tilde{E}) \tag{16}$$

Experience has shown that the bank angle profiles that result from the drag interpolation of Eq. (15) and Eq. (16) are flyable when D_{maxf} and D_{minf} are both flyable and appropriate values for k and $\tilde{E}_m$ are used for Eq. (15).

Feasible Bank Reversal Planning

In order for a trajectory to be feasible, bank sign reversals cannot occur instantaneously. A trajectory is modified to include a rate-limited bank reversal in the following manner. Starting from the value of $\tilde{E}$ where the reversal is scheduled to begin, the equations of motion are integrated using an open-loop constant rate bank reversal. After the reversal is complete, pre-tracking with the FBL plus PD drag tracking law is used to smoothly return the drag to the original curve. As during the computation of D_{maxf} and D_{minf}, $\zeta = 1$ is used along with the highest value of ω_n that maintains the overshoot below a small tolerated value. As before, the planner finds this value through an automated numerical search. The pre-tracking simulation is terminated once the drag error and the drag slope error are both below specified tolerances.

For low and medium crossrange entry scenarios, a second bank reversal is added near the end of entry to reserve some crossrange correction capability. In planning updates that occur before the first reversal is executed, the normalized energy at which the second reversal occurs is fixed. In these initial updates, P_2 controls the first bank reversal. After the first reversal has been executed, P_2 controls the remaining bank reversal. Unless an additional reversal is allowed, it is important that the second bank reversal is planned to occur near the target, because after it is executed, the planner loses its ability to target in crossrange. For entry cases that require high crossrange or for low-energy cases, a single bank reversal is sufficient if it will occur close enough to the target. The previous planner scheduled the two bank reversals in a slightly different manner, to similar effect.[9] However the new method that is described here eliminates one of the two parameters that were previously associated with adding a second bank reversal.

Planning Algorithm

The function of the planning algorithm is to generate a feasible entry trajectory. We have parameterized the final longitude and latitude with the parameters P_1 and P_2. The parameter $P_1 \in [0, 1]$ specifies the drag profile; the parameter $P_2 \in [0, 1]$ specifies the bank reversal initiation normalized energy. The target longitude and latitude values are denoted by (θ_f, ϕ_f). For the evaluation of the delivery error in longitude and latitude, the final position is expressed in "target frame" coordinates. The final 3D position is projected radially onto the sphere of radius r_f, where r_f is the target radius. The distance along the great circle containing the target final position, which is on this sphere, and the projected initial position is defined as downrange; whereas the crossrange distance, for a given downrange is measured along the great circle, on the same sphere, that intersects the downrange great circle perpendicularly. The downrange distance error is denoted by e_{dr}, with a positive value denoting an overshoot, the crossrange distance error by e_{cr}, with a positive value denoting an error to the right of the downrange great circle. Accordingly we write $e_{dr}(P_1, P_2)$ and $e_{cr}(P_1, P_2)$.

The problem solved by the planning algorithm is thus to determine (P_1, P_2) such that $e_{dr}(P_1, P_2) = 0$ and $e_{cr}(P_1, P_2) = 0$. The inputs to the algorithm are the boundary conditions on the state, the final energy E_f, the path constraint bounds $\bar{q}_{max}$, A_{max}, and $\dot{Q}_{max}$, a reference α profile, nominal models for C_D, ρ and g, and tolerances TOL_{dr} and TOL_{cr} for the downrange and crossrange errors. A successive approximation approach is used to determine the $(P_1,\ P_2)$ pair that nulls the downrange and crossrange errors. P_1 is adjusted in an outer-loop false position search to achieve the target downrange. Each time P_1 is updated during the search, an inner-loop determines the value of P_2 that minimizes the crossrange error. With this successive approximation approach, P_1 and P_2 are found using "nested" single-parameter searches instead of a two-parameter search. The false position searches converge to within an acceptable tolerance after several iterations. Approximately 50 to 100 $(P_1,\ P_2)$ pairs are tested during the process, which takes less than 2 seconds on current desktop computing hardware.

We first describe two key components of the algorithm – the false position search and the mapping from (P_1, P_2) to $e_{dr}(P_1, P_2)$ and $e_{cr}(P_1, P_2)$ – then we describe the algorithm.

False Position Search: For a scalar function $f(x)$, the problem is to determine c such that $f(c) = 0$ given a priori information that $c \in [a_0, b_0]$ and $sgn[f(a_0)] = -sgn[f(b_0)]$. The update equation is

$$c_k = \frac{a_k f(b_k) - b_k f(a_k)}{f(b_k) - f(a_k)} \tag{17}$$

If $sgn[f(a_k)] = sgn[f(c_k)]$, then $(a_{k+1}, b_{k+1}) = (c_k, b_k)$; otherwise, $(a_{k+1}, b_{k+1}) = (a_k, c_k)$. The search is initialized with $k = 0$ and continued until the iteration l when $|f(c_l)| < TOL$ is first satisfied, for a specified tolerance TOL. This search only has linear convergence, but we have found it to perform reliably.

Mapping: $(P_1, P_2) \to e_{dr}(P_1, P_2)$ and $e_{cr}(P_1, P_2)$

- Compute $r(E)$, $V(E)$, and $\gamma(E)$, and $L\cos(\sigma)$ from $D(E)$ and $\alpha(E) - r(E)$ from the second of Eqs. (2) and the nominal models for C_D and ρ, $V(E)$ from E and r, $\gamma(E)$ from the third of Eqs. (1) and a finite-difference approximation of $r'(E)$, and $L\cos\sigma$ from the fifth of Eqs. (1) with $C_\gamma = 0$.

- Integrate the first, second and fourth of Eqs. (1) using the $D(E)$, $\alpha(E)$, $r(E)$, $\gamma(E)$, $V(E)$, and $L\cos\sigma$ profiles, with $L\cos\sigma$ corrected at each integration step to account for C_γ. The magnitude of the lateral lift component is obtained as $|L\sin\sigma| = [L^2 - (L\cos\sigma)^2]^{1/2}$; the initial sign of the lateral lift component is selected so that the vehicle will turn toward the target, and a bank reversal is initiated at the normalized energy $\tilde{P}_2$ and handled as already described.

This procedure generates the complete entry trajectory; in particular it generates values of $e_{dr}(P_1, P_2)$ and $e_{cr}(P_1, P_2)$.

Planning Algorithm:

- Compute D_{min_f} and D_{max_f} and use either Eq. (15) or Eq. (16) to establish the P_1 parametrization. If Eq. (15) is used, the parameters k and $\tilde{E}_m$ must be specified.

- Outer-loop false position search for P_1 such that $e_{dr}(P_1, P_2) = 0$: the initial bounding values are 0 and 1, i.e., $(a_0, b_0) = (0, 1)$; subsequently P_1 is updated according to Eq. (17) with $f(P_1) = e_{dr}(P_1, P_2)$. The iterative search is stopped when $|e_{dr}(P_1, P_2)| < TOL_{dr}$.

- Inner-loop search for P_2 such that $|e_{cr}(P_1, P_2)|$ is minimized with P_1 fixed at the current value in the outer-loop search. If $sgn[e_{cr}(P_1, 0)] = sgn[e_{cr}(P_1, 1)]$, then $P_2 = 1$ is the minimizing value. Physically this is the case where the initial bank angle sign, chosen such that the vehicle is turning toward the target, remains appropriate for the whole trajectory. Because, with the given drag profile (determined by the value of P_1), the vehicle cannot achieve $e_{cr} = 0$. If on the other hand, $sgn[e_{cr}(P_1, 0)] = -sgn[e_{cr}(P_1, 1)]$, then execute a false position search for the value of P_2 that nulls $f(P_2) = e_{cr}(P_1, P_2)$. The search is initialized with $(a_0, b_0) = (0, 1)$ and is stopped when $|e_{cr}(P_1, P_2)| < TOL_{cr}$.

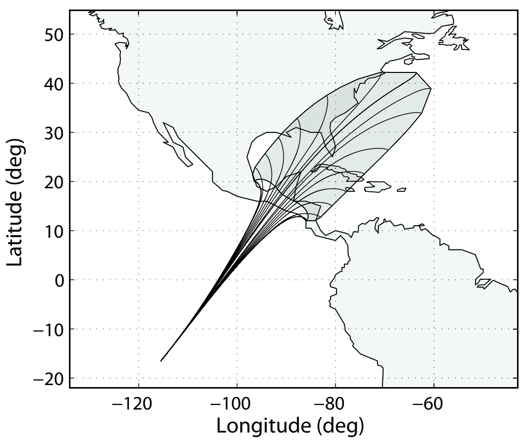
Similarities and Differences with Shuttle Approach

This algorithm is drag-based like the Shuttle approach. This features eases the handling of path constraints and limits the prediction sensitivity to phugoid-like motion. The vertical plane dynamics for r and γ are not integrated, except in the pre-tracking procedure to generate D_{min_f} and D_{max_f}, and to shape the transient following a bank reversal, where the phugoid-like motion is controlled by feedback. In contrast to the Shuttle approach, (i) rather than assuming r is constant and $\gamma = 0$, r and γ are deduced from D, (ii) the lateral motion is accounted for and a bank reversal is planned, (iii) a feasible trajectory is planned, and (iv) trajectories to most points in the landing footprint can be planned.

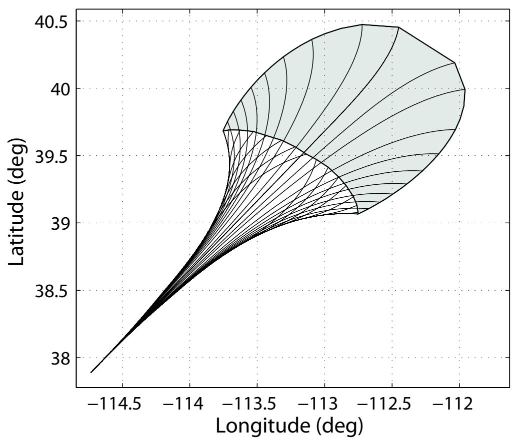
Performance Demonstrations

In this section the performance of the planner is demonstrated: first for landing footprint generation and second in the role of the planning function in EAGLE. For the purpose of these demonstrations, logic for deciding whether the case is high or low energy, or high or low-medium crossrange and executing the appropriate planning technique has not been automated in the planning algorithm we use. Development of a stand alone algorithm and validation via extensive simulation testing is outside the scope of this paper.

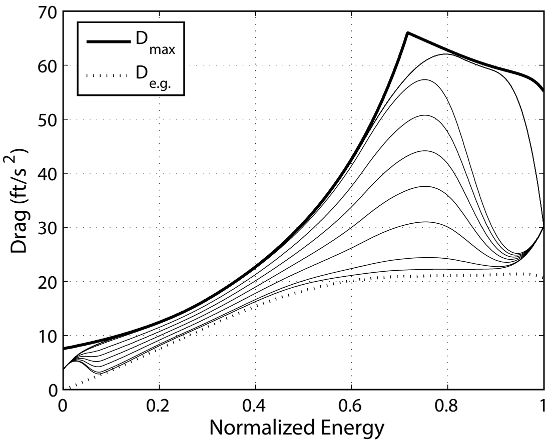
The results presented here are based on the vehicle model and initial entry conditions from the Advanced Guidance and Control (AGC) Project,[10] but using our own simulation rather than the one used in the AGC Project. The vehicle model is an enhanced model of the X-33. In the AGC testing for entry guidance, there were 9 orbital entry cases, labeled EG13 to EG21, and 19 suborbital cases labeled EG1 to EG12 and EG22



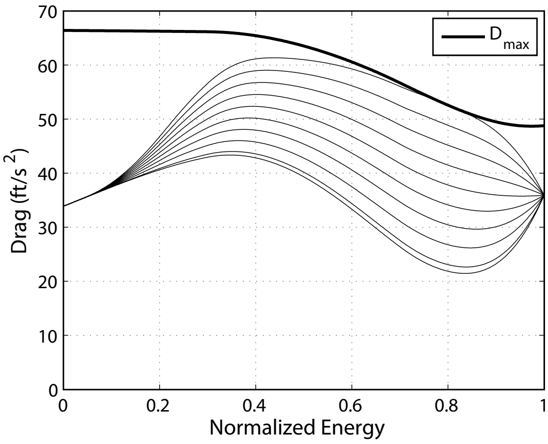
(a) EG16 landing footprint with ground tracks



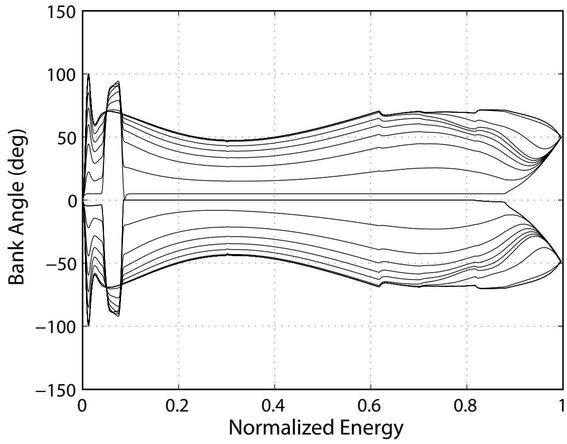
(b) EG3 landing footprint with ground tracks



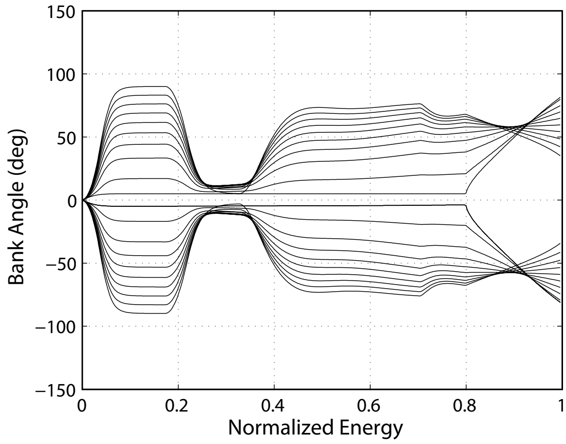
(c) EG16 drag



(d) EG3 drag



(e) EG16 bank angle



(f) EG3 bank angle

Figure 2. Trajectories from the new planner

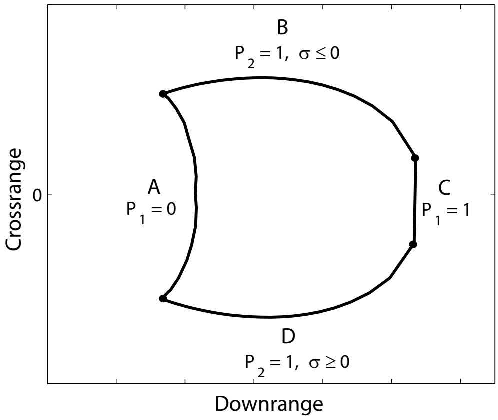


Figure 3. Landing footprint diagram

to EG28. Six of the 9 orbital cases test the high-crossrange guidance capability of the algorithms involved with respect to the baseline guidance algorithm, which was modeled after the Shuttle entry guidance.[2] The suborbital cases test the ability of the algorithms to deal with abort situations, including several involving mis-modeling and actuator failures. EAGLE, with its original planner, was submitted for testing in the AGC project and scored well overall.[9,10,21] Though EAGLE tested exceptionally well for all of the orbital cases, the scores were lower for several of the suborbital cases. This is due in large part to the factors that have motivated the development of the new planner.

The new planner is first demonstrated by using it for landing footprint generation. The set of final downrange and crossrange points that a planner can target for a given entry state is an approximation of the vehicle's landing footprint. The accuracy of the approximation depends on the planner that is used. By comparing the planner-generated footprints with the actual footprints, computed by trajectory optimization, one can determine how much of the actual footprint the planner is capable of covering.

To create a landing footprint, the mapping function of the new EAGLE planner is called repeatedly with varying values specified for P_1 and P_2. (No iteration to determine P_1 and P_2 is required, since there is no pre-specified target.) The endpoints of the resulting trajectories serve as the vertices of a polygon that represents the footprint approximation. The footprint has four basic sides, each a constant P_1 or P_2 curve (a piecewise linear curve due to the finite number of vertices), as diagrammed in Fig. 3. In the figure, sides B and D correspond to maximum crossrange ($P_2 = 1$), side C corresponds to maximum downrange ($P_1 = 1$), and side A corresponds to minimum downrange ($P_1 = 0$). Positive-crossrange trajectories are generated with a positive initial bank sign and negative-crossrange trajectories are created with a negative initial bank sign. (For entry guidance, only one initial bank sign is used – the one that initially turns the vehicle toward the target.)

Figure 2a and Fig. 2b show EAGLE-generated landing footprints for the EG3 and EG16 initial conditions. Ground tracks are shown in Fig. 2a and Fig. 2b for every third vertex of those that make up the footprint border polygons. Figure 2c and Fig. 2d show the drag profiles that correspond to the side boundary trajectories shown in Fig. 2a and Fig. 2b, respectively. In Fig. 2c, the drag profile just below D_{max} is D_{maxf}, and the profile just above $D_{e.g.}$ is D_{minf}. The interior profiles are obtained by interpolation according to Eq. (15) with the substitutions for P_1 and $\tilde{E}_m$ described in the previous section. In Fig. 2d, the drag profile just below D_{max} is D_{maxf}, and the lowest profile is D_{minf}. $D_{e.g.}$ is not shown since D_{minf} was obtained from $\sigma = \sigma_{min}$. The interior profiles are obtained by interpolation according to Eq. (16). Note that all of the drag profiles of the same plot start at the same value and slope and end at the same value, which comes from the planner matching V_0, h_0, γ_0, V_f, and h_f. In Fig. 2c, D_{minf} is slightly above $D_{e.g.}$ once it levels out. This is because $D_{e.g.}$ was calculated with an exaggerated lift coefficient, for reasons that were explained in the previous section.

Figure 2e and Fig. 2f show the bank profiles that are associated with the trajectories to the side boundary shown in Fig. 2a and Fig. 2b, respectively. The highest-magnitude bank profile in each subfigure corresponds to the D_{maxf} profile, and the lowest-magnitude bank profile in each subfigure corresponds to the D_{minf} profile. The drop in $|\sigma|$ that is seen in the D_{maxf} bank profiles of Figure 2f occurs because D_{maxf} is obtained through the pre-tracking of D_{max} by the planner. When D_{maxf} gets near D_{max}, the reduction in $|\sigma|$ causes D_{maxf} to level out. The bank profiles indicate the feasibility of the trajectories. They observe the limits on $|\dot{\sigma}|$ and $|\ddot{\sigma}|$ of 10 deg/s and 2 deg/s^2, respectively, and match $\sigma_0 = 0$, the initial bank angle.

Figure 4 shows the boundary of the optimal landing footprint for the EG16 initial entry state. The EAGLE footprint is shown in the figure as a transparent filled polygon. The EAGLE footprint is a close approximation of the optimal footprint. The optimal footprint achieves slightly greater downrange, due to the phugoid-like oscillatory motion that is seen in the optimal minimum drag profile (not shown here), in which D oscillates around $D_{e.g.}$. The initial undershooting of $D_{e.g.}$ is the main explanation for the extra range. Phugoiding after the initial undershoot does not completely balance out the extra range because the magnitude of the oscillation decreases steadily with time.

Due to the ability to plan feasible reference trajectories, the suborbital guidance performance of EAGLE with the new planner has improved considerably. Figure 5 shows a tracking simulation for the EG3 initial condition. The vehicle starts relatively close to the target, providing little time for the drag tracking to eliminate transients that would occur from the infeasibilities associated with the previous trajectory planner. As such, EG3 is a good case for demonstrating EAGLE with its new trajectory planner. Modeling errors are added to C_L, C_D, and ρ. EAGLE uses the nominal models, while perturbed versions are used in the simulation. A sinusoidal multiplicative error with low frequency is applied to C_D and C_L, with Mach number as the independent variable. In the simulation, the nominal C_D is multiplied by $1.025 + 0.025\ sin(M + 4.57)$, C_L is multiplied by $0.975 + 0.025\ cos(M + 4.57)$, and ρ is multiplied by 0.95. The simulation is 3-DOF, and the commanded control values are low-pass filtered to simulate the presence of an entry flight control system. The filter delays the bank angle and angle of attack commands by about one second. Figure 5a shows the drag tracking response. D starts below D_{ref} because α starts below α_{ref} (Fig. 5c). A discontinuous jump in the D_{minf} boundary occurs at 50 *sec*, indicating that the reference trajectory was updated at that time. This is expected since updates were scheduled to occur automatically every 50 *sec*. The discontinuity occurs because D_{minf} starts from the current reference state at a trajectory update. The tracking proves to be close enough for the final condition error tolerances. A three-segment linear-in-energy drag profile could not have been followed as closely. Figure 5b shows the commanded and reference bank angle profiles. One bank reversal can be seen to start at $t = 80$ s. Figure 5d shows approximately the second half of the ground track. The final range-to-HAC error is -2.2 n miles, which falls within the 3 n mile AGC project tolerance. The final heading-to-HAC error is -2.8 deg, which falls within the 5 deg AGC project tolerance. The final altitude error is -1300 ft, which falls within the 3000 ft AGC project tolerance. It should be noted that, though the final conditions fall within AGC tolerances, the test environment that we used was not the same as in the AGC study; and thus our results do not necessarily indicate how the algorithm would perform in that test environment.

Orbital tracking results are not shown due to space limitations, but the use of the new planner does not have a large impact on EAGLE's performance for the 9 orbital AGC cases, which was already very good. The previous planner produced trajectories that were sufficiently close to being feasible for AGC13 to AGC21, so the tracking function was able to compensate in those cases. For orbital entry, the new planner will have the largest impact on entry scenarios involving extreme downrange or crossrange targets that it can reach but the previous planner could not, and on scenarios where the previous planner would have created drag profiles that require unattainable values for γ'.

In all cases, landing footprint computation and trajectory planning took between 1 and 2 seconds (coded in C) on a Pentium 4, 2.8 GHz personal computer. For the trajectory planning results in this paper, the tolerances for terminating the successive approximation iterations were 3000 feet for downrange and 1000 feet for crossrange. Because much of the computation time is associated with determining D_{maxf} and D_{minf}, the computation time is not strongly dependent on the values of the tolerances. For example, tightening the downrange tolerance to 0.03 feet doubled the number of iterations required but the total computation time only increased from 1.63 s to 1.95 s.

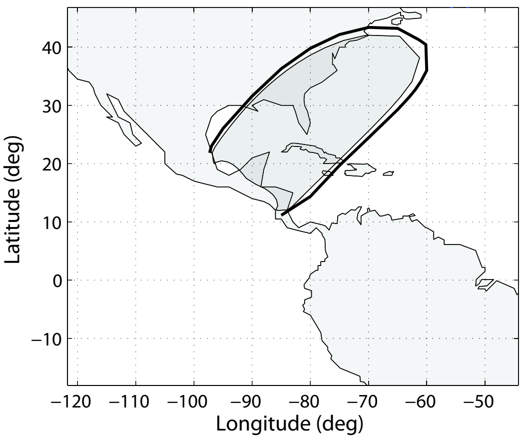
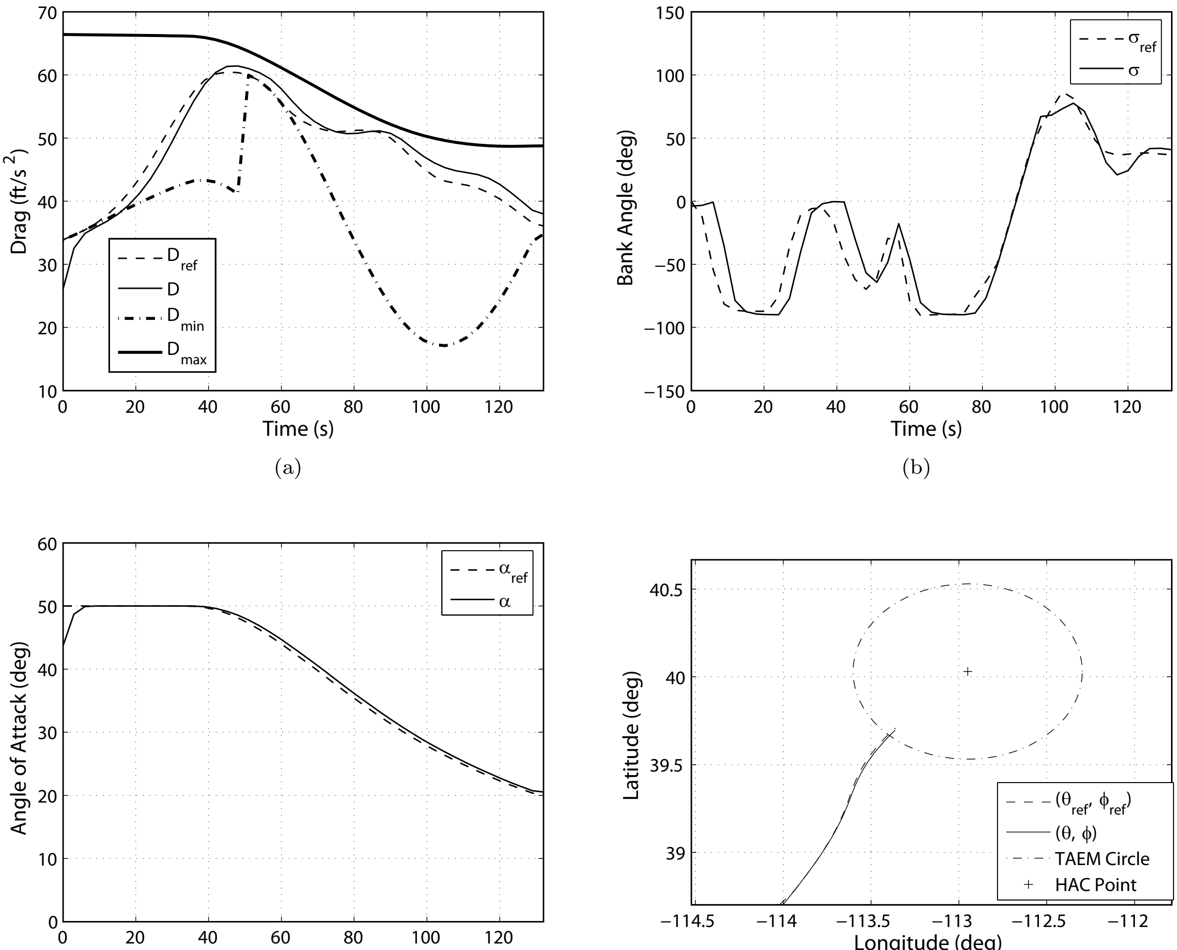


Figure 4. EG16 landing footprint shown inside of optimal footprint



(a) (b) (c) (d)

Figure 5. EG3 guidance simulation

Conclusions

An atmospheric entry trajectory planner has been developed that generates a feasible trajectory and associated bank angle profile. Feasibility ensures that the initial and final state conditions, the path and control constraints, and the nominal equations of motion are all satisfied. Feasible trajectories are easier to track; control saturation is less likely, as are path constraint violations. Guidance simulation results using an algorithm based on the planner demonstrated 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.

Acknowledgments

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