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Survey of planetary entry guidance algorithms

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ABSTRACT

This comprehensive literature survey reviews past and present planetary entry guidance algorithms. The algorithms are categorized based on the vehicle L/D and the planetary atmosphere that the vehicle is entering. Each algorithm is described based on the guidance type, the guidance formulation, and the inclusion of aerothermal parameters. An analysis was completed defining the performance of each guidance algorithm relative to one another within its specific category. Finally, an overall assessment was made regarding the state-of-the-art in spacecraft entry guidance.

Contents

1. Introduction

The entry guidance algorithm for lunar return of the manned Apollo capsule (1960s) was the first flight tested application of guidance. Since the pioneering efforts of Apollo guidance engineers, many algorithms have been developed for different missions and vehicles. However, there are no publications that comprehensively discuss the types of guidance algorithms and their formulations. This paper details past and present guidance algorithms in three categories: (1) high L/D, Earth entry spacecraft, (2) low- to mid-L/D, Earth entry spacecraft, and (3) other planetary entry spacecraft. In each category, the vehicle and entry trajectory type are defined, see Fig. 1 for an illustration of different vehicle types. Entry trajectories include aerocapture, direct entry, lofted entry, and skip entry. It should be noted that the objective of an

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Nomenclature

D	drag acceleration (ft/s^2)
D_f	drag force (lbf)
$\vec{F}$	force vector (lbf)
F_t	total force orthogonal to velocity vector (lbf)
F_t	total force parallel to velocity vector (lbf)
g	gravitational acceleration [ft/s^2]
h	altitude (ft)
L	lift acceleration [ft/s^2]
L_f	lift force (lbf)
m	vehicle mass (lbm)
R	magnitude of the radial distance vector for 3RSP model (ft)
$\vec{R}$	radial distance vector (ft)
t	time (s)
T_p	propulsive force (lbf)
V	relative velocity (ft/s)
x	downrange (nmi)
y	crossrange (nmi)
ϵ	angle between $\vec{v}_r$ and $\vec{F}$ (deg)
ϕ	declination (deg)
γ	flight path angle (deg)
θ	longitude (deg)
σ	bank angle (deg)
$\vec{\Omega}$	planet's rotation vector (1/rad)
ψ	azimuth (deg)
ACRV	assured crew return vehicle
AOTV	aeroassist orbit transfer vehicle
CAV	common aero vehicle
COV	calculus of variations
HEMS	high entry mass systems
MaRV	maneuvering re-entry vehicle
MER	Mars exploration Rover-class
MOrb	Mars 2001 orbiter
MSP	Mars surveyor program
SC	sphere cone

aerocapture trajectory is to meet a desired orbit, while a direct/lofted/skip trajectory is performed to target a specific landing site on the planet surface, but both require a guidance algorithm to be meet these targets.

Typically, guidance algorithms developed for Low L/D (<0.5) vehicles fly short range trajectories with moderate payloads ($\sim$5000 kg). Guidance algorithms, developed for high L/D (≥ 1.0) spacecraft can fly a longer cross range, perform a runway landing, and carry very large payloads to the ground (upwards of 10,000 kg). Guidance algorithms for Mid-L/D (≥ 0.5 and <1.0) vehicles have been of recent interest because larger payloads can be guided to the ground while maintaining low heat rates and low deceleration at higher altitudes. Although the reachable range for entry is dependent on guidance, it is more of a direct function of the spacecraft capability and the entry trajectory type. Some well known examples of low L/D spacecraft are Apollo, Mars Science Laboratory (MSL), and SpaceX's Dragon Capsule. The only high L/D spacecraft that has been extensively flight tested and used is NASA's now retired Space Shuttle, whereas most others are experimental. Mid L/D spacecraft are currently being examined for future high mass missions to Mars. There are other advancements in the works with the increase in the commercialization of space and developments in military hypersonics projects. However, many of these advanced guidance algorithms have yet to be published in publicly available journals.

This paper begins with an introduction to the field of entry guidance and then discusses the various models used to model entry flight dynamics. Finally, a comprehensive discussion of the state-of-the art in entry guidance is documented and discussed.

2. Fundamentals of entry guidance development

The construct for analysis of past and present guidance algorithms is derived from the process of guidance algorithm development. Guidance development can be a relatively subjective process as there are numerous ways to use the equations of motions and numerous requirements for a given mission.

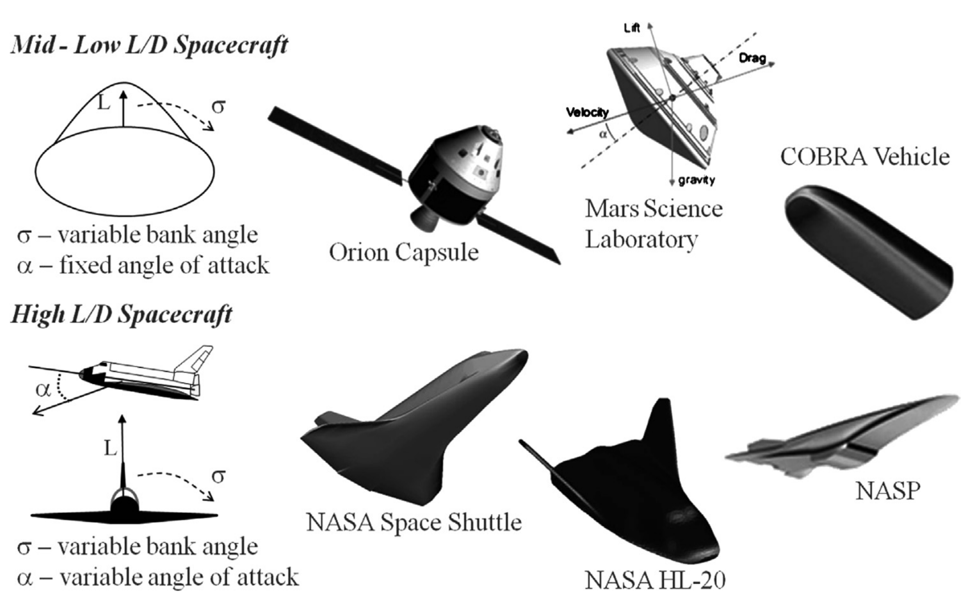

Fig. 1. Shape and available controls for different vehicle shapes.