

Atmospheric Interface Reentry Point Targeting Using Aerodynamic Drag Control

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DOI: 10.2514/6.2014-1000884

The ability to control the location of a spacecraft atmospheric interface reentry has been traditionally accomplished using propulsion. A novel technique is presented here where a predefined point of atmospheric interface reentry is achieved by adjusting the aerodynamic drag of a spacecraft in a circular orbit. If this method is employed at a sufficiently high starting altitude, any ground-track point accessible by the orbit can be targeted. This method can be broken up into two different parts. The first consists of finding the decay profile that achieves the desired reentry location. The second consists of keeping the spacecraft within this nominal decay trajectory, given the atmospheric uncertainty and other perturbations. The two parts of this method are presented here in detail. Finally, a case study is provided to demonstrate how this method could work in a realistic scenario and to evaluate its performance. The case study shows that a reentry point can be targeted with a 3 σ error of less than 200 km, using a typical Global Positioning System for navigation. Finally, a discussion of potential applications is provided.

Nomenclature

A_{ref}	=	spacecraft's reference area, m ²
a	=	semimajor axis, m
a_D	=	acceleration due to drag, m/s ²
C_B	=	ballistic coefficient, m ² /kg
C_D	=	drag coefficient
H	=	atmospheric scale height, m
h	=	altitude, m
i	=	orbit inclination, rad
J_2	=	Earth's oblateness coefficient
m	=	spacecraft mass, kg
n	=	mean motion, rad/s
q	=	dynamic pressure, N/m ²
t	=	time, s
θ	=	argument of latitude, rad
V	=	relative velocity of the flow, m/s
x	=	state vector
λ	=	longitude, rad
μ	=	gravitational constant of the Earth, m ³ /s ²
ρ	=	atmospheric density, kg/m ³
Φ	=	state transition function
ϕ	=	latitude, rad
Ω	=	right ascension of the ascending node, rad

1. Introduction

THE aerodynamic forces experienced by spacecraft orbiting in low Earth orbit are usually considered perturbations that need to be avoided or compensated. Although this is generally the case, these aerodynamic forces can be controlled and exploited to achieve a useful purpose. Research has already been conducted to use aerodynamic drag to perform an aerocapture, control a spacecraft orbit, rendezvous with another vehicle, do formation flight, and do constellation maintenance [1–8]. Also, the use of aerodynamic forces has also been studied to control the attitude of a spacecraft [9–11].

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Here a novel method is presented where the aerodynamic drag is used to target the atmospheric interface reentry point of a spacecraft's decaying orbit. The method presented here has been only applied to circular orbits and its extension to eccentric orbits is left for future studies. The assumption of circular orbits is not only applied to the initial orbit, but is also enforced as the orbit decays. It is also important to note that the method presented here only controls the location of the atmospheric interface reentry point and not the landing or impact point (if the spacecraft was to survive reentry). The atmospheric interface reentry point, also known as the entry interface in the literature, can be defined as the point where the interaction of the spacecraft with the atmosphere is so great, in terms of aerodynamic forces, that these forces completely dominate the flight dynamics. The altitude when this occurs depends on the vehicle aerodynamic properties and the atmospheric conditions, but it is usually set between 120–90 km [12]. Here an intermediate altitude of 100 km has been selected.

The control of the aerodynamic drag is assumed to be achieved through the control over the ballistic coefficient. Therefore, the drag is modulated to achieve the desired decay rate at all times. How to control the ballistic coefficient of a spacecraft and its practical considerations are outside the scope of this paper, but it is not difficult to envision simple ways to do so. For example, changing the cross-sectional area of the spacecraft by changing the attitude of the spacecraft or by altering the geometry of a drag sail would do.

Changing the ballistic coefficient, by changing the cross-sectional area, for example, is enough to alter the drag that the spacecraft creates, but it is not enough to have knowledge of this drag. The knowledge of the atmospheric properties (mainly density) is required to bridge the gap between controlling the ballistic coefficient and controlling the drag. This information of the atmospheric conditions can be obtained by using atmospheric models (estimation) or by using in situ measurements by onboard sensors. A detailed analysis of how to obtain this information has also been left outside the scope of this paper.

The idea of using drag to control certain parameters of the atmospheric interface reentry location is not completely new. Some work has been done to use a sudden drag increase in the last few hours of the decay to reduce the uncertainty of the time and location of the reentry interface [13]. The same approach is taken in [14] where a sudden increase in drag in the last few orbits is used to make the spacecraft reenter over an unpopulated area and reduce the risk to population and property that any surviving parts that reach the ground might pose. These two works, using the same method, only provide a limited capability to change the atmospheric interface reentry location in the along-track direction. Because this is done close to the reentry interface, the accessible targets are limited to the locations defined (approximately) by the last few orbits' ground track (along track). The method presented here starts modulating the drag at much

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Hayabusa2 Asteroid Sample Return Mission Masatoshi Hirabayashi, Yuichi Tsuda, 2022-04-14 Hayabusa2 Asteroid Sample Return Mission Technological Innovation and Advances covers the second Japanese asteroid sample return mission. The purpose of the mission is to survey the asteroid Ryugu's surface features, touch down on the asteroid, form an artificial crater by shooting an impactor, and collect sample materials. This book covers these operations along with everything known about key technologies, hardware, and ground systems upon Hayabusa2's return to Earth in 2020. This book is the definitive reference on the mission and provides space and planetary scientists with information on established technologies to further advance the knowledge and technologies in future space exploration missions. 2023 PROSE Awards Winner Finalist. Chemistry, Physics, Astronomy, and Cosmology Association of American Publishers. Broadly and comprehensively covers technologies necessary for space exploration missions. Provides a unique focus on small body exploration missions. Covers landing and impact experiments during the proximity operations of Hayabusa2. *Fiscal Year 1973 Authorization for Military Procurement, Research and Development, Construction Authorization for the Safeguard ABM, and Active Duty and Selected Reserve Strengths, Hearings ...*, 92-2 ... United States. Congress. Senate. Armed Services, 1972. **U.S. Marines In Vietnam: The War That Would Not End, 1971-1973** Melson, Charles D., 2018-09-17 U.S. Marines In Vietnam: The War That Would Not End, 1971-1973. Charles D. Melson, Curtis G. Arnold. United States Marine Corps History and Museums Division. This is the eighth volume of a projected nine-volume history of Marine Corps operations in the Vietnam War. A separate functional series complements the operational histories. This volume details the activities of Marine Corps units after the departure from Vietnam in 1971 of III Marine Amphibious Force through to the 1973 ceasefire and includes the return of Marine prisoners of war from North Vietnam. Written from diverse views and sources, the common thread in this narrative is the continued resistance of the South Vietnamese Armed Forces, in particular the Vietnamese Marine Corps, to Communist aggression. This book is written from the perspective of the American Marines who assisted them in their efforts. Someday the former South Vietnamese Marines will be able to tell their own story. **U.S. Marines in Vietnam: The war that would not end, 1971-1973** United States. Marine Corps. History and Museums Division, 1991. *U.S. Marines in Vietnam* Charles D. Melson, Curtis G. Arnold, 1991. **4th ESA International Conference on Spacecraft Guidance, Navigation and Control Systems and Tutorial on Modern and Robust Control: Theory, Tools and Applications B.** Schürmann, European Space Agency, 2000. **Journal of the British Interplanetary Society**, 1975. **International Aerospace Abstracts**, 1997. **Technical Information Indexes**, 1974. **Aviation Week & Space Technology**, 1997. *Daily Report*, 1996. *44th Congress of the International Astronautical Federation*, 1993. *Guidance and Control*, 1998. **Space/aeronautics**, 1969. **Aviation Space Dictionary** Ernest James Gentle, 1980. Dissertation Abstracts International, 2002. **Technical Abstract Bulletin**, 1980. **Tech Notes**, 1984. Congressional Record United States.

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