Aerospace Science and Technology 75 (2018) 172–182

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

# Optimal fuel consumption finite-thrust orbital hopping of aeroassisted spacecraft

Runqi Chai [a], Al Savvaris [a], Antonios Tsourdos [a], Senchun Chai [b,*], Yuanqing Xia [b]

[a] School of Aerospace, Transport and Manufacturing, Cranfield University, Bedfordshire, MK43 0AL, United Kingdom
[b] School of Automation, Beijing Institute of Technology, Beijing 100081, PR China

ARTICLE INFO

*Article history:*
Received 11 June 2017
Received in revised form 15 November 2017
Accepted 19 December 2017
Available online 3 February 2018

*Keywords:*
Aeroassisted spacecraft
Orbital hopping
Optimal control
Trajectory optimization

ABSTRACT

In the paper, the problem of minimum-fuel aeroassisted spacecraft regional reconnaissance (orbital hopping) is considered. A new nonlinear constrained optimal control formulation is designed and constructed so as to describe this mission scenario. This formulation contains multiple exo-atmospheric and atmospheric flight phases and correspondingly, two sets of flight dynamics. The constructed continuous-time optimal control system is then discretized via a multi-phase global collocation technique. The resulting discrete-time system is optimized using a newly proposed gradient-based optimization algorithm. Several comparative simulations are carried out and the obtained optimal results indicate that it is effective and feasible to use the proposed multi-phase optimal control design for achieving the aeroassisted vehicle orbital hopping mission.



## 1. Introduction

In the past few decades, aeroassisted orbital transfer vehicles have received considerable attention due to their extensive applications in space exploration [1–3]. One important advantage of using this type of flight vehicle is that it has the capability to apply the aerodynamic forces and its engine model effectively [1,4]. Early works on developing the aeroassisted spacecraft mainly focus on the propulsion and online guidance systems [5–7]. For example, in [8], the authors proposed an online minimum energy-loss guidance strategy for the aeroassisted vehicle. Naidu et al. [9] designed a neighboring optimal guidance scheme for the nonlinear aeroassisted vehicle dynamics. Meanwhile, many important research works focusing on the aeroassisted vehicle orbital transfer have been extensively investigated [4,10]. Specifically, Darby and Rao [11] considered a small-scale spacecraft orbital transfer problem using impulsive thrust. In their work, the entire mission was completed during the space flight. Begum et al. [12] designed the aeroassisted orbital transfer trajectory based on the optimal control theory. Different with the work carried out in [11], both the space flight and atmospheric pass were used to complete the mission in [12].

Although the aforementioned research works show the potential feasibility and benefits of using the aeroassisted vehicle for the orbital transfer, less attention has been paid to apply the aeroassisted vehicle for an orbital hopping or regional reconnaissance mission profile. Therefore, in this paper, a new aeroassisted spacecraft orbital hopping problem formulation is proposed and studied. The main objective of this work is to generate the minimum-fuel trajectory for the orbital hopping mission. Then based on the obtained optimal solutions, a better understanding in terms of the performance requirements and the structure of the problem can be gained.

The overall optimal fuel consumption aeroassisted vehicle orbital hopping problem is formulated as a multiple-phase nonlinear optimal control problem. This type of problem is becoming an active topic since the obtained optimal reference trajectory can be implemented in various industrial applications [13–16]. To calculate the optimal solution, a typical direct transcription algorithm (e.g. Gauss pseudospectral method [17,18]) is applied to discretize the vehicle dynamics. In recent years, global collocation techniques have attracted extensive attentions and a large amount of work is being carried out in this field [3]. For example, Fahroo and Ross [19] developed a Chebyshev pseudospectral approach for solving the general Bolza trajectory optimization problems with control and state constraints. In their follow-up work [20], a pseudospectral knotting algorithm was designed so as to solve nonsmooth optimal control problems. The main advantage with pseudospectral methods is that a high approximation accuracy can be achieved with much less temporal nodes [18,21]. After generating the opti-

* Corresponding author.
*E-mail addresses:* r.chai@cranfield.ac.uk (R. Chai), a.savvaris@cranfield.ac.uk (A. Savvaris), a.tsourdos@cranfield.ac.uk (A. Tsourdos), chaisc97@bit.edu.cn (S. Chai), xia_yuanqing@bit.edu.cn (Y. Xia).

https://doi.org/10.1016/j.ast.2017.12.026
1270-9638/

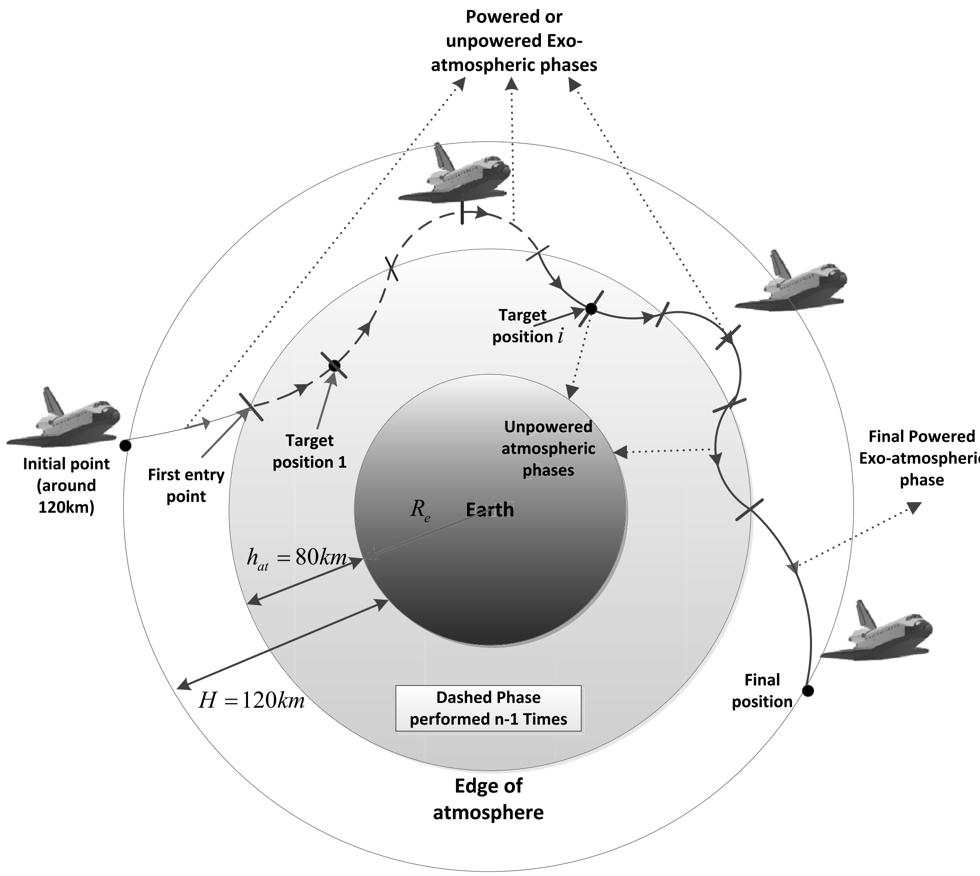


**Fig. 1.** Aeroassisted vehicle orbital hopping mission profile.

mal solutions, the results are analyzed to show the key features of the constructed problem in the simulation section.

The rest of this paper is organized as follows: In Section 2, a new minimum-fuel aeroassisted spacecraft orbital hopping mission is proposed and formulated. In order to guide the vehicle overflying different ground target positions, a series of event sequences are constructed and embedded in the problem formulation. Section 3 gives a brief description in terms of the direct algorithm used to calculate the optimal solution. The main results are provided in Section 4, where comparative simulations verify the effectiveness and feasibility of the proposed design philosophy. The concluding remark is given in Section 5.

## 2. Aeroassisted spacecraft reconnaissance optimal control problem

The mission scenario investigated in this research focuses on the atmospheric skip hopping, targeting the entry into the atmosphere down to different predetermined positions for observation and gathering of information of inaccessible areas. Once these positions are reached, the spacecraft starts the ascent phase, exiting the atmosphere and returning back to Low Earth Orbit (LEO). During the mission, the aeroassisted spacecraft can fly in either the unpowered exo-atmospheric flight, powered exo-atmospheric flight, or unpowered atmospheric flight. The overall mission profile is illustrated in Fig. 1.

It is worth noting that as shown in Fig. 1, the dashed line phases may repeat several times (e.g. $n-1$ times). This is because in this paper, it is expected for the aeroassisted vehicle to have a multiple-hop trajectory in order to overfly different target regions and complete the reconnaissance mission. An example of a single-hop mission can be found in our previous work [22].

### 2.1. Vehicle equations of motion

The dynamics of the aeroassisted vehicle is modeled as a point mass over a spherical rotating Earth. For the exo-atmospheric flight, the effect caused by aerodynamic forces can be ignored and the differential equations of motion are defined as [23,24]:

$$\begin{cases} \dot{r} = V\sin\gamma \\ \dot{\theta} = \frac{V\cos\gamma\sin\psi}{r\cos\phi} \\ \dot{\phi} = \frac{V\cos\gamma\cos\psi}{r} \\ \dot{V} = \frac{T\cos\alpha}{m} - g\sin\gamma + \omega_V \\ \dot{\gamma} = \frac{T\sin\alpha}{mV} + (\frac{V^2-gr}{rV})\cos\gamma + \omega_\gamma \\ \dot{\psi} = \frac{V}{r}\cos\gamma\sin\psi\tan\phi + \omega_\psi \\ \dot{m} = -\frac{T}{I_{sp}g} \end{cases} \tag{1}$$

where $r$, $\theta$, $\phi$, $V$, $\gamma$, $\psi$, $m$ represent the radial distance, longitude, latitude, velocity, flight-path angle, heading angle and vehicle's mass, respectively. $\alpha$ is the angle of attack and $T$ is the thrust force. During unpowered flight phases, $T$ is set to zero. The gravity $g = \frac{\mu}{r^2}$, in which $\mu$ is the gravitational parameter. $I_{sp}$ is the specific impulse. $\omega_V$, $\omega_\gamma$ and $\omega_\psi$ stand for the contribution of Coriolis acceleration and convected acceleration. Their analytical expressions can be given by

$$\begin{cases} \omega_V = \Omega^2 r\cos\phi(\sin\gamma\cos\phi - \cos\gamma\sin\psi\cos\psi) \\ \omega_\gamma = 2\Omega\cos\phi\sin\psi \\ \qquad + \Omega^2 r\cos\phi(\cos\gamma\cos\phi + \sin\gamma\cos\psi\sin\phi) \\ \omega_\psi = \frac{\Omega^2 r\cos\phi\sin\phi}{\cos\gamma} - 2\Omega(\tan\gamma\cos\psi\cos\phi - \sin\phi) \end{cases} \tag{2}$$