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Multi-objective trajectory optimization of Space Manoeuvre Vehicle using adaptive differential evolution and modified game theory

Runqi Chai[a], Al Savvaris[a], Antonios Tsourdos[a], Senchun Chai[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

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ABSTRACT

Highly constrained trajectory optimization for Space Manoeuvre Vehicles (SMV) is a challenging problem. In practice, this problem becomes more difficult when multiple mission requirements are taken into account. Because of the nonlinearity in the dynamic model and even the objectives, it is usually hard for designers to generate a compromised trajectory without violating strict path and box constraints. In this paper, a new multi-objective SMV optimal control model is formulated and parameterized using combined shooting-collocation technique. A modified game theory approach, coupled with an adaptive differential evolution algorithm, is designed in order to generate the pareto front of the multi-objective trajectory optimization problem. In addition, to improve the quality of obtained solutions, a control logic is embedded in the framework of the proposed approach. Several existing multi-objective evolutionary algorithms are studied and compared with the proposed method. Simulation results indicate that without driving the solution out of the feasible region, the proposed method can perform better in terms of convergence ability and convergence speed than its counterparts. Moreover, the quality of the pareto set generated using the proposed method is higher than other multi-objective evolutionary algorithms, which means the newly proposed algorithm is more attractive for solving multi-criteria SMV trajectory planning problem.

1. Introduction

In the future, it is very likely that Space Manoeuvre Vehicles (SMV) are going to play an increasingly important role in s7pace exploration. Therefore, a well-planned trajectory, particularly in skip entry phase, is key to stable flight and improved guidance control of the vehicle [1–6]. Unlike studies investigated in most of literatures [1,7], where the re-entry problem was addressed, the mission scenario studied in this paper focuses on the atmospheric skip hopping, targeting the entry into the atmosphere down to a predetermined position (predetermined altitude was set at the start of this project to specifically address this type of mission) and the required controls involved in returning back to low Earth orbit. Commonly, these types of trajectory planning problem can be described as an optimal control problem and numerical methods are usually applied to calculate the near-optimal solution [8].

Numerical methods for solving trajectory optimization problems are divided into two major classes: indirect methods and direct methods [9–13,8]. However, it is difficult to solve the trajectory design problem using indirect methods, since the maximum principle is required to be derived. Therefore, direct optimization method has been widely used for trajectory optimization. Among direct methods, one traditional technique which has been used in practical problems is direct multiple shooting method [1,4,14]. The main process of the direct multiple shooting method is to parameterize only the control variables using interpolation at discretized time nodes. In recent years, collocation methods for discretizing optimal control problems have increased in popularity. Unlike shooting methods, collocation techniques parameterize both the state and control variables. There are two kinds of collocation methods, local collocation method (e.g. the direct collocation) and global collocation method (e.g. the pseudospectral method [15]). Two well-known pseudospectral methods for solving trajectory optimization problems are the Legendre pseudospectral method [16,11,12,17] and the Chebyshev pseudospectral method [18,19]. Compared with multiple shooting method, collocation methods tend to result in large scale optimization parameters and it has not been used in real application to date. A main reason is that current onboard computational devices may fail to satisfy the requirement of the large computational time needed for these algorithms. Therefore, a hybrid multiple shooting scheme is proposed in this paper. This method can keep the advantages of using collocation scheme but not

* 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).

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result a large scale nonlinear programming problem so that the computational burden of the optimizer can be reduced.

In most of existing studies, the trajectory planning problem usually aims at one single objective, for example, minimizing the aerodynamic heating, maximizing the final velocity, etc. However, most of the real-world design problems encountered by aerospace engineers involve simultaneous optimization of several competitive objective functions [20–22]. For the mission considered in this paper, the expectations for enhancing performance and saving cost are of significant importance. Therefore, it is desired to have a multi-objective SMV model with multiple criteria so as to capture more of the real-world requirements. There are many multi-objective methods, which are suitable for these kind of problems. Since the solution of multi-objective programming problem is not unique (known as nondominated solution), multi-objective evolutionary algorithms are commonly implemented to generate all the potential solutions (also known as pareto set) [23–28]. Deb et al. [23] developed the Nondominated Sorting Genetic Algorithm (NSGA2) using a nondominated sorting procedure and the crowding distance metric, and in [29], NSGA2 method was applied to generate the pareto front of a multi-objective re-entry trajectory optimization problem. Li et al. [21] applied a Multi-objective Evolutionary Algorithm Based on Decomposition (MOEA/D) method to solve general multi-objective problems. However, from the previous works, it was analyzed that the computational burden of iterative optimization is heavy and the quality of obtained solution still needs to be improved. Hence, in this paper, an adaptive differential evolution based on modified game theory algorithm is designed. By applying the control logic, the quality of the generated solution can be improved. Moreover, in order to enhance the convergence ability, a modified game theory is introduced and coupled in the algorithm framework.

It is worth noting that one practical use of the obtained theoretic results is that it can be applied to design the online guidance law or used as the reference command for the online tracking algorithm [7,5]. The main advantage for tracking these reference trajectories is that all the reference results can satisfy the constraints and multiple mission-dependent objectives can be optimized. Since the pareto front information can be calculated by applying the proposed Multi-objective trajectory optimization method, the decision makers can have more flexibility to do the decision-making based on the presented relationships between different conflicting objective functions.

Hereafter, the paper is organised as follows. In Section 2, a new 3-DOF continuous-time optimal control model including different types of constraints and objective functions is established and parameterized using the hybrid multiple shooting method. Following that, Section 3 presents the framework of proposed adaptive differential evolution and modified game theory algorithm. Compromised solutions generated by employing the proposed method and different evolutionary multi-objective approaches are given in Section 4. The paper ends with Section 5, the conclusions.

2. Problem formulation

The skip entry can be divided into five phases: initial roll, down control, up control, Kepler and final entry. Considering the mission of the SMV is to overfly the ground target with specific altitude, the most challenging down control and up control will be considered in this paper. The overall mission is illustrated in Fig. 1.

2.1. Dynamic model

Taking the rotation of the Earth into account, the 3-DOF equations of motion of the Space Manoeuvre Vehicle are constructed by the following set of Ordinary Differential Equations (ODEs):

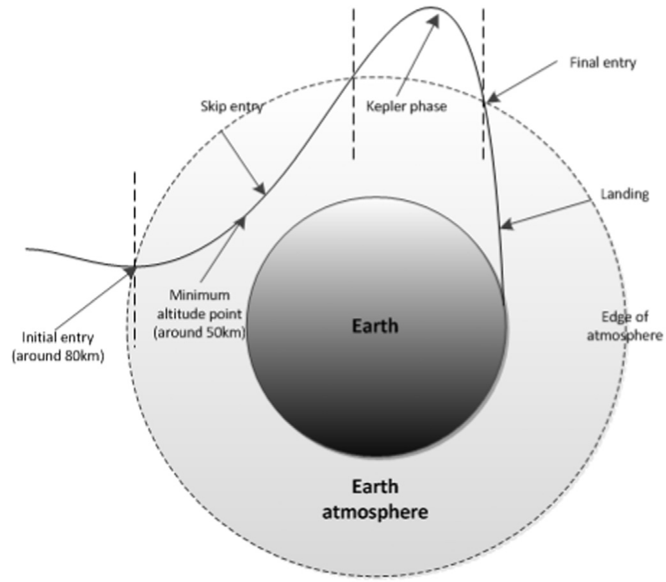

Fig. 1. General mission profile.

$$\dot{r} = V\sin\gamma \dot{\theta} = \frac{V\cos\gamma\sin\psi}{r\cos\phi}\dot{\phi} = \frac{V\cos\gamma\cos\psi}{r}\dot{V} = \frac{T\cos\alpha - D}{m} - g\sin\gamma + \Omega^2 r\cos\phi(\sin\gamma\cos\phi - \cos\gamma\sin\phi\cos\psi)\dot{\gamma} = \frac{L\cos\sigma + T\sin\alpha}{mV} + \left(\frac{V^2 - gr}{rV}\right)\cos\gamma + 2\Omega\cos\phi\sin\psi + \Omega^2 r\cos\phi(\cos\gamma\cos\phi + \sin\gamma\cos\psi\sin\phi)V^{-1}\dot{\psi} = \frac{L\sin\sigma}{mV\cos\gamma} + \frac{V}{r}\cos\gamma\sin\psi\tan\phi + \frac{\Omega^2 r\sin\psi\cos\phi\sin\phi}{V\cos\gamma} - 2\Omega(\tan\gamma\cos\psi\cos\phi - \sin\phi)\dot{m} = -\frac{T}{I_{sp}g} \quad (1)$$

where r is the distance from the center of the earth, θ and ϕ are the longitude and latitude, respectively. V is the relative velocity, γ is the flight path angle. ψ is the relative velocity heading angle measured clockwise from the north, m is the mass of vehicle. The control variables are angle of attack α, bank angle σ and thrust T, respectively. The earth's rotation rate is $\Omega = 7.2921151e^{-5}$ rad/s.

The atmosphere and aerodynamic model can be summarised as:

$$g = \frac{\mu}{r^2} \qquad \rho = \rho_0 \exp\frac{r - r_{e0}}{h_s}$$
$$L = \frac{1}{2}\rho V^2 C_L S \qquad D = \frac{1}{2}\rho V^2 C_D S$$
$$C_D = C_{D0} + C_{D1}\alpha + C_{D2}\alpha^2 \quad C_L = C_{L0} + C_{L1}\alpha \quad (2)$$

where $S = 249.91$ m^2 is reference area, ρ is the density of the atmosphere and $\rho_0 = 1.2250$ kg/m^3 is the density of the atmosphere at sea-level. $r_{e0} = 6378.135$ km is earth radius, L and D are the lift and drag whereas C_L and C_D are the corresponding lift and drag coefficients. g is the gravitational acceleration. Although g can be treated as a constant, to make the problem more realistic, it is assumed that the gravitational acceleration is varying with respect to the altitude.

A detailed description in terms of the entry reference frames and aerodynamic forces can be found in Fig. 2.

In the model given by Eq. (1), three autopilot equations are introduced by using the technique of first order lag [30] to describe the rate constraint of the controls,

$$\dot{\alpha} = K_\alpha(\alpha_c - \alpha)\dot{\sigma} = K_\sigma(\sigma_c - \sigma)\dot{T} = K_T(T_c - T) \quad (3)$$

where α_c, σ_c and T_c are the demanded angle of attack, bank angle and thrust, respectively. Correspondingly, three new control constraints should be introduced.

$$\alpha_{c(min)} \le \alpha_c \le \alpha_{c(max)}\sigma_{c(min)} \le \sigma_c \le \sigma_{c(max)}T_{c(min)} \le T_c \le T_{c(max)} \quad (4)$$