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A novel robust hybrid gravitational search algorithm for reusable launch vehicle approach and landing trajectory optimization

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ABSTRACT

The approach and landing (A&L) trajectory optimization is a critical problem for secure flight of reusable launch vehicle (RLV). In this paper, the A&L is divided into two sub-phases, glide phase and flare phase respectively. The flare phase is designed firstly based on the desired touchdown (TD) states. Then, the glide phase is optimized using a proposed novel robust hybrid algorithm that combines advantages of the gravitational search algorithm (GSA) and gauss pseudospectral method (GPM). In the proposed hybrid algorithm, an improved GSA (IGSA) is presented to enhance the convergence speed and the global search ability, by adopting the elite memory reservation strategy and an adaptive gravitational constant adaption with individual optimum fitness feedback. At the beginning stage of search process, an initialization generator is constructed to find an optimum solution with IGSA, due to its strong global search ability and robustness to the initial values. When the change in fitness value satisfies the predefined value, the IGSA is replaced by the GPM to accelerate the search process and to get an accurate optimum solution. Finally, the Monte Carlo simulation results are analyzed in detail, which demonstrate the proposed method is practicable. The comparison with GSA and GPM shows that the hybrid algorithm has better performance in terms of convergence speed, robustness and accuracy for solving the RLV A&L trajectory optimization problem.

1. Introduction

In order to meet the increasing demand for space utilization, reusable launch vehicle (RLV) is developed to provide the potential way to improve space vehicle economics. Since the approach and landing (A&L) is the last phase of the RLV's returning to the earth [1], it is a critical flight phase that brings the unpowered RLV from the end of the terminal area energy management (TAEM) flight to the runway touchdown (TD), which makes the safety to be the primary and enforcing requirement [2,3]. The present literatures imposed most efforts on the development of new approaches that could deliver a RLV to its landing TD site safely and reliably [1,4,5]. Among those, the research on the A&L trajectory optimization has been proved to be a very significant issue for the secure landing [6].

During the A&L trajectory optimization, there are some enforcing physical constraints that must be concerned [5], such as dynamic pressure, vertical descent rate, continuity and smoothness. The vehicle's structural strength determines the dynamic pressure cannot beyond the specific maximum values restricted; and the decreasing vertical descent rate before the runway TD is demanded, which makes sure the vehicle touches the runway softly with an acceptable descent rate in case of fiercely strike; meanwhile, the limited time and space in the A&L determine the RLV's limited control ability and limited adjustment ability, so the change rate of the controls and the states during the entire flight phase are desired as small as possible, namely the continuity and smoothness of the control and state trajectories should also be concerned strictly. Besides the constraints above, the boundary constraints (the initial and final point constraints of the flight phase to be optimized) are also required to be satisfy the accurately of landing.

It is now well established that many of the challenges on trajectory optimization fall under the purview of optimal control theory [6], and difficulties in solving nonlinear optimal control (NOC) problems have reflected difficulties in solving the trajectory optimization problem [7]. The enforcing constraints, as described above, reduce the NOC problem of the trajectory optimization to a Hamiltonian two point boundary value problem (HBVP) with conditions on initial and final states [5]. In recent decades, many numerical methods based on gradient information have been widely used to solve the HBVP [8–11]. The numerical methods

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are generally concluded as two distinct branches: indirect methods and direct methods [8], both of which try to minimize the cost functions and constraint violations by using discrete approximations of the parameters in the system. Compared to the indirect methods, direct methods for solving NOC problem have become increasing popular [9]. In a direct method, the continuous-time nonlinear optimal control problem is transcribed to a nonlinear programming problem (NLP), and the resulting NLP can be solved numerically by well-developed algorithms, which attempt to satisfy a set of conditions associated with the NLP. Within the class of the direct methods, the pseudospectral methods, especially the gauss pseudospectral method (GPM) [10, 11], has been proved to be more competitive in the numerical accuracy, computational efficiency, and ease of using. Compared to class optimal theory, the GPM have advantages in flexible applicability to complex problems, relative faster convergence speed of search process and higher accuracy of the optimum solution. While, like other numerical methods, the GPM is also featured with the drawbacks of lacking robustness to the initial guess values and getting trapped at local optimum easily [12].

Since the poverty-stricken to trap at local optimum and the sensitivity to initial guess of the numerical methods in handling the complex NOC problems, other approaches aiming at obtaining the global optimum solution has been researched. Over the last decades, heuristic optimization algorithms, such as the differential evolution (DE) [13], genetic algorithms (GA) [14] and particle swarm optimization (PSO) [15] etc., have been proposed. Due to their better global search ability, non-sensitive to the initial guess and no need for function's gradient information, the heuristic optimization algorithms have been successfully used in many complex NOC problems [16–20]. However, as reported in [21], some disadvantages of GA are still needed to be overcome and one of the main problems is premature convergence due to a loss of population diversity at a suboptimal point. Although PSO is a successful stochastic optimization algorithm, it may track into local minima and thus could not obtain better solution [22]. In a word, the searching ability of an optimization algorithm, including accuracy and efficiency, decides its potential in solving complex engineering problems, including NOC problem for complex nonlinear system.

In recent years, a new optimization method known as gravitational search algorithm (GSA) proposed by Rashedi et al. [23] has become a candidate for optimization application due to its flexibility and efficiency, which is based on the Newton's law of gravity and law of motion. It is a heuristic algorithm similar to PSO and the swarm intelligence instructed optimization research is produced by cooperation and competition among swarms in colony. GSA has been well applied in UAV path planning problem [24] and many other specific optimizations problems [25–27]. It has been proved to possess a better global search performance in a serial of optimization problems, compared with PSO algorithm and GA [27]. However, like other heuristic optimization algorithms, the proposed GSA also lacks of effective convergence acceleration mechanism and shows poorer ability in the convergence accuracy compared to numerical methods [24,28].

Because each agent direction is calculated based on the overall force obtained by other agents (that means all the agents' information in the current iteration is utilized in each agent's evolution), GSA shows great search ability to the global optimum solution and robustness to random initial values. And for the same reason, the GSA is memory-less, the convergence speed (both at the search beginning and around the global optimum) will also be limited. Conversely, although the GPM features poor robustness to the initial guess values, it can get faster convergence speed around global optimum and higher convergence accuracy with the initial guess properly selected.

For these reasons described above, some novel works is completed in this paper.

First, the model of RLV A&L is formulated, then A&L trajectory is divided into glide phase and flare phase due to the its particularity in practical terms. The flare phase is firstly designed using exponential flare strategy [5] based on the desired TD states, and the trajectory optimization of the glide phase will be solved using the hybrid algorithm to be proposed.

Second, an improved GSA (IGSA) is proposed in this paper to further enhance the global search ability and convergence speed. On the one hand, the elite memory reservation strategy is introduced in GSA to get a superior global search performance, which is achieved by introducing the elite's positions (the best position of all the agents) that have ever reached so far into the speed evolution equation of GSA. On the other hand, as the gravitational constant has great effect on the convergence speed, an adaptive gravitational constant adaption in the force evolution is proposed to accelerate the convergence speed of the global search adaptively. The individual optimum fitness is taken as a kind of feedback to the gravitational constant in the force evolution process, and the gravitational constant is set as a function of individual optimum fitness. Therefore, a big gravitational constant is obtained at the beginning of searching due to the far distance between the agents and the optimum solution, while a small gravitational constant can be got after finding a near optimum solution to the near distance between the agents and the optimum solution.

Third, a novel hybrid algorithm IGSA–GPM that combines the improved GSA (IGSA) and GPM is proposed to solve the trajectory optimization problem of A&L glide phase. The fundamental idea in the proposed hybrid algorithms can be described as follows. At the beginning stage of searching for the optimum, the GSA is used to find an approximate optimum solution and to accelerate the global search. When the change in fitness value is smaller than a predefined value, the searching process is switched to GPM which achieves faster convergence speed around the global optimum and higher accuracy [9,10,28,29]. Meanwhile, the best solution found by IGSA will be taken as the initial starting values for the NLP solver in GPM. The results show that the proposed IGSA–GPM has higher efficiency and accuracy for solving the RLV A&L trajectory optimization problem, the convergence speed and accuracy is satisfactory, and the robustness to initial guess values is also optimistic.

The paper is organized as follows. Section 2 describes the formulation of RLV A&L trajectory optimization problem. In Section 3, the classical GSA theory is presented, then the adaptive gravitational constant with individual fitness feedback and the elite's memory information are introduced to GSA, and IGSA is proposed. A brief description of GPM for solving the optimal problem is presented in Section 4. Section 5 introduces the theory and procedure of the hybrid IGSA–GPM algorithm in detail. Section 6 applies the hybrid algorithm to RLV A&L trajectory optimization problem, and the simulations of IGSA with other heuristic algorithms and the hybrid IGSA–GPM are conducted. Finally, conclusions are given in Section 7.

2. RLV approach and landing trajectory optimization problem formulation

In this section the dynamic model of the RLV A&L is presented. Assuming zero cross range to the runway, the unpowered RLV is considered a point mass, the approach and landing phase of an RLV in a single vertical plane can be modeled as follows [1]:

$$\dot{V} = -D/m - g \sin \gamma \tag{1}$$