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Precise halo orbit design and optimal transfer to halo orbits from earth using differential evolution

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Abstract

The mission design to a halo orbit around the libration points from Earth involves two important steps. In the first step, we design a halo orbit for a specified size and in the second step, we obtain an optimal transfer trajectory design to the halo orbit from an Earth parking orbit. Conventionally, the preliminary design for these steps is obtained using higher order analytical solution and the dynamical systems theory respectively. Refinements of the design are carried out using gradient based methods such as differential correction and pseudo arc length continuation method under the of circular restricted three body model. In this paper, alternative single level schemes are developed for both of these steps based on differential evolution, an evolutionary optimization technique. The differential evolution based scheme for halo orbit design produces precise halo orbit design avoiding the refinement steps. Further, in this approach, prior knowledge of higher order analytical solutions for the halo orbit design is not needed. The differential evolution based scheme for the transfer trajectory, identifies the precise location on the halo orbit that needs minimum energy for insertion and avoids exploration of multiple points. The need of a close guess is removed because the present scheme operates on a set of bounds for the unknowns. The constraint on the closest approach altitude from Earth is handled through objective function. The use of these schemes as the design and analysis tools within the of circular restricted three body model is demonstrated through case studies for missions to the first libration point of Sun–Earth system.

Keywords: Lagrangian point; Halo orbit design; Optimal transfer; Restricted three body problem; Differential correction; Differential evolution

1. Introduction

The observations from the periodic orbits around libration points are expected to unravel many mysteries surrounding the universe. The spacecrafts placed around the Sun–Earth L_1 point can monitor the solar activity and the orbits about the Sun–Earth L_2 point offer a good option for space observatories for deep space exploration. The orbits around the Earth–Moon libration points have been proposed as suitable for communication between Earth and the far side of the moon. The Earth–Moon L_2 point has been found to be ideal for setting up a propellant depot for innovative space transportation. Farquhar et al. (2004) present a comprehensive study consolidating the future mission plans utilizing the libration points. Development of a design method that minimizes the energy for transferring the spacecraft from an Earth parking orbit is an important step. The advances in numerical methods together with the advent of high speed computers have made the detailed study of the three body problem possible.

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Nomenclature

A_Z	out-of plane amplitude of the halo orbit, km
CR	crossover frequency
CR3BP	circular restricted three body problem
F	mutation scale factor
m_1	mass of first primary body
m_2	mass of second primary body
m_3	mass of third body
N	population size
n	number of unknowns
r_1	radial distance of third body from 1st primary, normalized units
r_2	radial distance of third body from 2nd primary, normalized units
T	time period of the halo orbit, normalized units
$\mathbf{X}$	state vector of the spacecraft
x, y, z	position components of the space craft in barycentric coordinate frame
$\dot{x}, \dot{y}, \dot{z}$	velocity components of the space craft in barycentric coordinate frame

Abbreviations

CAA	closest approach altitude, km
DC	differential correction
DE	differential evolution
DST	dynamical system theory
EPO	earth parking orbit
STM	state transition matrix

Subscripts

0	correspond to initial instant of time
$T/2$	corresponds to the half-period of the halo orbit
T	corresponds to the period of the halo orbit

Ever since the success of ISEE-3 mission to the Sun–Earth libration point L_1 (Farquhar et al., 1977, 1980), many researchers developed various design methodologies for the transfer to halo orbits from Earth. The mission design to halo orbits involves two major steps: (i) the design of halo orbit and (ii) the design of an optimal transfer trajectory to the halo orbit from an Earth parking orbit satisfying certain objectives. The halo orbit design is conventionally carried out using analytical solutions initially and then refined using a differential correction (DC) scheme. It is well known that any DC scheme needs a good initial guess. Richardson (1980) developed the third order analytical solution for the halo orbit design. But, when numerically integrated under the CR3BP model, this design is not periodic. However, using this closed form solution as the initial guess, the DC scheme refines the design to make it periodic. The formulation based on the DC scheme needs one of the unknown coordinates to be fixed at a value, obtained using higher order analytical solution (Richardson, 1980). Because of this fixation of a variable, the resulting refined halo orbit design will not have the same out-of-plane amplitude that is used in Richardson solution. To achieve exact halo orbit characteristics another level of refinements based on pseudo arc-length continuation method (Paffenroth et al., 2000) is required.

For the transfer trajectory design, three types of design processes (Folta and Beckman, 2002) have been used: i) determining the initial conditions of the transfer trajectory near Earth through forward propagation and by numerical search ii) determining the transfer trajectory conditions starting from the halo orbit by numerical search through backward propagation iii) choosing a suitable manifold that goes near Earth from the family of stable manifolds originating from the halo orbit generated using dynamical systems theory [DST]. In the design process followed in Farquhar et al. (1977) and Sharer and Harrington (1996), initial guess is made on the initial conditions of the transfer trajectory starting from an Earth parking orbit. These initial conditions are refined by numerical search using an optimization technique. Many sets of initial conditions are propagated forward and for those sets which reach halo orbit, the halo orbit insertion velocity is computed. Finally, the set of initial conditions that results in minimum insertion cost is selected. In these studies, the halo orbit enters in the design process as a boundary condition to be achieved at the end of the propagation and this boundary condition is taken as a specific known point viz. X–Z plane crossing of the halo orbit. Rodriguez-Canabal and Hechler (1989) generated the transfer trajectory by choosing a location on the halo orbit and adding a velocity impulse, and then numerically propagating backwards to reach the Earth parking orbit. For the numerical search, gradient based optimization techniques such as recursive quadratic programming and conjugate gradient method have been used in these studies. The well known complexity of optimization using gradient based method is discussed by these authors (Rodriguez-Canabal and Hechler, 1989). In a major turnaround, Gomez et al. (1993), demonstrated the use of DST and the stable manifolds of the periodic (halo) orbits for the transfers from Earth to the halo orbits. This procedure provides in-depth insight into the transfer scenarios. The stable manifolds from the halo orbit that go near the Earth on backward numerical integration are considered as candidates for transfer trajectories. So, the problem of transfer to halo orbits became identifying the right manifold that meets the mission requirements and transferring the spacecraft into this manifold. However, further investigations revealed that the manifolds from the smaller