Acta Astronautica 112 (2015) 1–18

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Review

Incorporating the evolution of multi-body orbits into the trajectory trade space and design process ☆

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A R T I C L E   I N F O

Article history:
Received 17 February 2015
Accepted 18 February 2015
Available online 26 February 2015

Keywords:
Circular restricted three-body problem
Poincaré maps
Invariant manifolds
Libration point orbits

A B S T R A C T

Libration point orbits have been incorporated in many missions, with the capability of orbiting near L_1 and L_2 in the Earth–Moon system recently demonstrated during the ARTEMIS mission. While the orbits in the vicinity of the collinear libration points have been well studied, knowledge about the availability and evolution of these orbits is not generally exploited during the mission design process. In this investigation, strategies to display information about the global solution space in the vicinity of the libration points are explored, facilitating a rapid assessment of the available solutions for a range of energy levels. A design process is presented that exploits information about the available orbit structures, and is demonstrated for several sample design scenarios, including transfers to and between libration point orbits.

Contents

☆ This paper was presented during the 65th IAC in Toronto.

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http://dx.doi.org/10.1016/j.actaastro.2015.02.024

1. Introduction

Within the last several decades, libration point orbits have been incorporated into many missions as, for example, the Sun–Earth L_1 and L_2 points prove quite useful for solar and cosmological observatories. The capability of executing a libration point mission in the Earth–Moon system was recently demonstrated during the ARTEMIS mission, where the impact of solar radiation in the lunar vicinity was examined as the Moon moved into and out of the Earth's magnetosphere. The orbits in the vicinity of the libration points have been well studied, providing a wealth of information about the available orbits and their evolution [1–8]. This information can be leveraged during the mission design process. For example, stability information associated with the GENESIS mission orbit was exploited to compute the invariant manifolds employed for the transfer design [9]. However, knowledge about the solution space is not generally exploited in current trajectory design tools. Collection and exploitation of this information within the design process would prove valuable to assess the available orbits against the design requirements, to consider possible trade-offs between the various orbit types, and to inform the selection of orbits that meet the mission constraints.

As mission requirements become increasingly complex, trajectory design tools that take advantage of the available natural dynamics are essential. Several tools exist that exploit dynamical systems theory for mission design, including Generator [10,11] and LTool [12]. A tool to interactively compute libration point orbits and their associated manifolds is demonstrated by Mondelo et al. [13]. The AUTO software allows for computation of periodic orbits, numerical continuation of orbit families, as well as bifurcation detection and analysis [14]. An Adaptive Trajectory Design (ATD) strategy was demonstrated by Haapala et al., and provides interactive access to a variety of solutions for rapid design and analysis of trajectory options [15]. A dynamic reference catalog is introduced by Folta et al. as well as Guzzetti et al., and offers an interactive environment for orbit comparison and selection [16,17].

In this investigation, strategies to display information about the global solution space in the vicinity of the libration points are explored, and their incorporation into the mission design process is demonstrated. Several distinct periodic and quasi-periodic orbit types are available in the vicinity of a libration point, and each may offer different advantages. As parameters, such as the Jacobi constant, change in value, the solution space evolves and the available orbits can be modified significantly. An overview of the current knowledge about this evolution is summarized, and a framework for the global solution space is charted, facilitating a rapid assessment of the available periodic and quasi-periodic solutions over a range of energy levels. A design process that exploits this information is demonstrated for several sample design scenarios.

2. Circular restricted three-body model

The Circular Restricted Three-Body (CR3B) problem [18] is a simplified model that offers insight about libration points and their associated orbits. In many cases, a preliminary design constructed within the framework of the CR3B can be transitioned to a higher-fidelity ephemeris model while maintaining the significant qualitative features of the original solution. In the Earth–Moon CR3B problem, the motion of a spacecraft, assumed massless, is determined by the gravitational forces of the Earth and the Moon, each represented as a point mass. The orbits of the Earth and Moon are assumed to be circular relative to the system barycenter. A barycentric rotating frame is defined such that the rotating x-axis is directed from the Earth to the Moon, the z-axis is parallel to the direction of the angular velocity of the primary system, and the y-axis completes the right-handed, orthonormal triad. The position of the spacecraft is defined relative to the Earth–Moon barycenter, and the six-dimensional state vector is written in terms of rotating coordinates as $\boldsymbol{x} = [x, y, z, \dot{x}, \dot{y}, \dot{z}]$. The mass parameter is defined as $\mu = m_2/(m_1+m_2)$, where m_1 and m_2 correspond to the mass of the Earth and Moon, respectively. The first-order, nondimensional, vector equation of motion is

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}), \tag{1}$$

where the vector field, $\boldsymbol{f}(\boldsymbol{x})$, is defined

$$\boldsymbol{f}(\boldsymbol{x}) = \left[\dot{x}, \dot{y}, \dot{z}, 2n\dot{y}+U_x, -2n\dot{x}+U_y, U_z\right], \tag{2}$$

noting that the nondimensional mean motion of the primary system is $n=1$. In Eqs. (1)–(2), $U(x,y,z,n) = (1-\mu)/r_{13}+\mu/r_{23}+\frac{1}{2}n^2(x^2+y^2)$ is the pseudo-potential function, where the nondimensional Earth–spacecraft and Moon–spacecraft distances are written as r_{13} and r_{23}, respectively, and the quantities U_x, U_y, U_z represent partial derivatives of U with respect to rotating position coordinates. The only known integral of the motion is the Jacobi constant, evaluated as $C = 2U - v^2$, where $v = \left(\dot{x}^2+\dot{y}^2+\dot{z}^2\right)^{1/2}$. This quantity is a constant of the motion and offers useful information about the energy level associated with a given solution in the CR3BP.

3. Collinear libration points

The equations of motion described by Eqs. (1) and (2) admit five equilibrium points, including three collinear points that lie along the x-axis, and two equilateral points. Linearization about any collinear libration point reveals an eigenvalue structure of the type saddle $\times$ center $\times$ center [6,18,19]. A pair of real roots, $\pm\sigma$, correspond to the one-dimensional stable and unstable manifolds. Two pairs of imaginary roots, $\pm i\nu$ and $\pm i\omega$, indicate that the center