Acta Astronautica 126 (2016) 439–455

Contents lists available at ScienceDirect

Acta Astronautica

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

Rapid trajectory design in the Earth–Moon ephemeris system via an interactive catalog of periodic and quasi-periodic orbits[☆]

Davide Guzzetti [a,*], Natasha Bosanac [a], Amanda Haapala [a,1], Kathleen C. Howell [a], David C. Folta [b]

[a] School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN, USA
[b] National Aeronautics and Space Administration/Goddard Space Flight Center, Greenbelt, MD, USA

ARTICLE INFO

Article history:
Received 22 February 2016
Accepted 16 June 2016
Available online 18 June 2016

Keywords:
Multi-body systems
Three-body problem
Libration points
Quasi-periodic solutions
Periodic solutions

ABSTRACT

Upcoming missions and prospective design concepts in the Earth–Moon system extensively leverage multi-body dynamics that may facilitate access to strategic locations or reduce propellant usage. To incorporate these dynamical structures into the mission design process, Purdue University and the NASA Goddard Flight Space Center have initiated the construction of a trajectory design framework to rapidly access and compare solutions from the circular restricted three-body problem. This framework, based upon a 'dynamic' catalog of periodic and quasi-periodic orbits within the Earth–Moon system, can guide an end-to-end trajectory design in an ephemeris model. In particular, the inclusion of quasi-periodic orbits further expands the design space, potentially enabling the detection of additional orbit options. To demonstrate the concept of a 'dynamic' catalog, a prototype graphical interface is developed. Strategies to characterize and represent periodic and quasi-periodic information for interactive trajectory comparison and selection are discussed. Two sample applications for formation flying near the Earth–Moon L_2 point and lunar space infrastructures are explored to demonstrate the efficacy of a 'dynamic' catalog for rapid trajectory design and validity in higher-fidelity models.

1. Introduction

With the increasing complexity of space mission proposals, there is significant interest in trajectory design approaches that require fewer resources and deliver results sustainable over long term scenarios. Such goals may be achieved by leveraging the natural dynamical structures in the Earth–Moon system to guide the selection of a baseline path. A well-informed trajectory design process that incorporates natural multi-body structures may be particularly beneficial for several upcoming mission concepts including exoplanet observatories, in situ exploration of asteroids as well as redirect concepts, and lunar CubeSat missions [1–5]. The design of a baseline trajectory is nontrivial in a dynamically sensitive environment. In fact, in a higher-fidelity multi-body regime, the comparison of a large set of candidate solutions demands significant, and often prohibitive, time and computational resources. However, the well-studied Circular Restricted Three-Body Problem (CR3BP) can provide a reasonable approximation to the actual dynamical environment. The dynamical structures available in this model have been successfully leveraged by several missions in the Sun–Earth system as well as in early demonstrations in the Earth–Moon system [6–8].

For rapid trajectory design in a multi-body regime, knowledge of the dynamical structures in a conceptual model may facilitate a better understanding of the design space than a set of point solutions in the complete ephemeris model. Many software packages, for example, AGI's Systems Tool Kit (STK) and NASA's General Mission Analysis Tool (GMAT), offer a graphical environment for trajectory design incorporating gravitational fields at various levels of fidelity [9,10]. However, the focus of these packages is generally directed towards the delivery of trajectory point designs and other operational mission support capabilities. Thus, they may be not specifically structured to offer guidance and insight into the available dynamical structures throughout the region. To supply a framework for incorporating knowledge of the dynamical accessibility in the Earth–Moon system, Purdue University and NASA Goddard Space Flight Center have been developing an interactive adaptive design process exploiting a reference catalog of solutions from the CR3BP to enhance efficient trajectory design in such

☆The original version of this paper was presented during the IAF 66th International Astronautical Congress in Jerusalem, Israel, in October 2015.

* Corresponding author.
E-mail addresses: dguzzett@purdue.edu (D. Guzzetti), nbosanac@purdue.edu (N. Bosanac), amanda.haapala@jhuapl.edu (A. Haapala), howell@purdue.edu (K.C. Howell), david.c.folta@nasa.gov (D.C. Folta).
[1] Currently at Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723, USA.

http://dx.doi.org/10.1016/j.actaastro.2016.06.029
0094-5765/© 2016 IAA Published by Elsevier Ltd. All rights reserved.

complex environments. In this simplified model, periodic and quasi-periodic orbits govern the underlying dynamics and are approximately retained in higher-fidelity models [7,11–14]. The current effort is focused on creating direct links between the problem understanding and its practical application by exploring the Earth–Moon design space. There exists a wide array of known orbits with significant potential for parking, staging and transfers within the Earth–Moon system. Previously developed software tools, e.g., AUTO, can also supply a selection of these solutions as well as some insight into the local dynamics and the evolution of a set of orbits along any family [15]. In particular, AUTO enables the computation of periodic orbits and their numerical continuation into orbit families, as well as the detection and analysis of bifurcations. Nevertheless, such tools do not offer a basic 'blueprint' to support rapid, efficient and well-informed decisions regarding the use of fundamental solutions in multi-body dynamical environments for any mission scenario prior to an end-to-end trajectory design.

To overcome the challenges associated with identifying candidate trajectories in a chaotic multi-body regime, the available dynamical structures may be explored interactively. Previous studies on the application of interactive visual analytics to trajectory design have been conducted by Schlei for various applications in multi-body regimes [16]. In addition, a prototype software to assemble trajectories via point-and-click arc selection in multi-body scenarios is introduced by Haapala et al. [17]. This design suite, Adaptive Trajectory Design (ATD), offers an interactive interface to facilitate exploration of mission design options. First, the dynamics in the Earth–Moon and Sun-Earth systems are approximated using the CR3BP. Dynamical structures in the form of periodic and quasi-periodic orbits and manifolds may be computed on-demand to construct an initial guess for an end-to-end trajectory, along with maneuvers. Ultimately, the constructed initial guess can be corrected both in the CR3BP and in an ephemeris model, and even exported to NASA's GMAT [10]. As a supplement to ATD, a 'dynamic' catalog has been constructed to identify and characterize periodic orbits that may aid in trajectory design and selection within the Earth–Moon system [18]. This information, as well as a preliminary classification of orbits, are compiled into a graphical environment allowing the user to directly interact with data types that cannot be adequately represented by a static set of tabular data. As a result, a 'dynamic' and interactive catalog may overcome some of the challenges associated with constructing a predefined trade space to analyze a large set of solutions for a general mission concept [19].

In this investigation, the Earth–Moon catalog of periodic solutions is expanded to include nearly bounded motion. Quasi-periodic motion, which inherits the behavior of a nearby periodic orbit, further expands the set of design options, thereby allowing identification of trajectories that may satisfy the mission requirements when transitioned to an ephemeris model. Families of quasi-periodic solutions are precomputed numerically and sampled to construct a representative set, which the user can immediately access in the catalog [20,21]. While a quasi-periodic orbit may partially retain the characteristics of a nearby periodic solution, it may also possess unique and independent features that may be exploited in the mission design process. Accordingly, quasi-periodic motions are characterized in terms of quantities that may be used for a preliminary evaluation of the mission constraints. The utilization of this information within a graphical user interface is discussed and a prototype is demonstrated via application to a sample mission concept involving a formation of spacecraft near the Earth–Moon L_2 point.

2. Dynamical background

The rapid and intuitive exploration of the dynamical structures in the Earth–Moon system is first based on the CR3BP. This dynamical model, which serves as a reasonable approximation to the actual gravitational field, reflects the motion of a massless spacecraft under the influence of the point-mass gravitational attractions of the Earth and Moon. These two primary bodies are assumed to move in circular orbits about their mutual barycenter. The motion of the vehicle is described relative to a coordinate frame, $\hat{x}\hat{y}\hat{z}$, that rotates with the motion of the Earth and Moon. In this frame, the spacecraft is located by the nondimensional coordinates (x, y, z). By convention, quantities in the CR3BP are nondimensionalized such that the Earth–Moon distance, as well as the mean motion of the primaries, are both equal to a constant value of unity. In addition, the Earth and Moon have nondimensional masses equal to $1-\mu$ and μ, respectively, where μ equals the ratio of the mass of the Moon to the total mass of the system. In the rotating frame, the equations of motion for the spacecraft are written as:

$$\ddot{x} - 2\dot{y} = \frac{\partial U}{\partial x},\ \ddot{y} + 2\dot{x} = \frac{\partial U}{\partial y},\ \ddot{z} = \frac{\partial U}{\partial z} \tag{1}$$

where the pseudo-potential function, $U = \frac{1}{2}(x^2 + y^2) + \frac{1-\mu}{d} + \frac{\mu}{r}$, while $d = \sqrt{(x+\mu)^2 + y^2 + z^2}$ and $r = \sqrt{(x-1+\mu)^2 + y^2 + z^2}$. This gravitational field admits five equilibrium points: the collinear points L_1, L_2, and L_3 are located along the Earth–Moon line; and two equilateral points, L_4 and L_5, form equilateral triangles with the two primaries. Since the CR3BP is autonomous, a constant energy integral exists in the rotating frame and is equal to the Jacobi constant, JC:

$$JC = 2U - \dot{x}^2 - \dot{y}^2 - \dot{z}^2 \tag{2}$$

At any specific value of the Jacobi constant, there are infinite possible trajectories exhibiting a wide array of behaviors. However, any trajectory may be generally classified as one of four types of solutions: equilibrium point, periodic orbit, quasi-periodic orbit, and chaotic motion. Each of these solutions can be identified using numerical techniques and subsequently characterized using concepts and quantities from dynamical systems theory.

3. Catalog of periodic orbits

To capture the dynamical structures available in the CR3BP, families of periodic orbits are exploited. The parameters describing a periodic orbit generally reflect characteristics of the nearby dynamics, potentially indicating the presence of additional structures, such as nearby manifolds or bounded motions. The characterization and classification of families of periodic solutions is, therefore, valuable in creating an efficient framework for mission design and preliminary mission trade-offs [19].

The catalog adopts a classification system for periodic orbits using concepts that are most generally accepted in the astrodynamics community. Families of periodic orbits in the CR3BP are gathered into four classes: libration point orbits (LPO), resonant orbits (RES), Moon-centered orbits (P2), and Earth-centered orbits (P1). Classes are designated according to the dynamical origin of the families. For instance, orbits identified as LPO emanate from the vicinity of the equilibrium points, such as the samples of axial, halo, Lyapunov, and vertical families in Fig. 1(a). Families of resonant orbits, i.e., RES families, include orbits that possess an integer ratio between the orbital period and the period of the Moon's motion around the Earth; a resonance denoted as p:q, indicates that the Moon completes p revolutions about the Earth