Mubody, an astrodynamics open-source Python library focused on libration points

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Abstract

Mubody is an astrodynamics open-source Python library focused on the libration points. Such points result from the equilibrium of the gravitational forces between two massive bodies as the Sun and Earth, for example. The library is mainly intended for the generation of orbits in these regions, which is not a straightforward process, specially if perturbations are considered. Currently, the library allows to generate Lissajous orbits in the second Lagrange point of the Sun-Earth system under the influence of perturbations such as the Earth orbit eccentricity. The next milestone, as a result of a master student work, is the incorporation of Halo orbits and the expansion to all three collinear libration points from any two massive bodies of the Solar System. This tool has been developed as part of a PhD, motivated by the need of performing mission analysis in libration point regions. Nevertheless, since its creation it has also proven to be an excellent academic tool for both enhancing the library itself and using its results for further studies (collision risk, thermal analysis, formation flight control, etc). As a result, the tool has rapidly evolved, building onto the knowledge and experience that the students gather while working on their academic projects (bachelor's degree dissertations, master theses, subjects, internships). The participation on the library development provides students with experience in orbital mechanics, software design, version control and it compels them to ensure that their work can be readily used by others as it is properly documented. The project is hosted in GitLab under a MIT licence.

Keywords

Astrodynamics, Libration Points, Python, mission analysis, education, open-source

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Nomenclature

Δv	*Delta-v of maneuvers*
μ	*CRTBP mass parameter*
ρ_i	*Distance to primary i*
G	*Gravitational constant*
m_i	*Mass of the celestial body i*
r_i	*Position vector to celestial body i*
U	*Pseudo-potential function*

Acronyms/Abbreviations

CRTBP	*Circular Restricted Three Body Problem*
ERTBP	*Elliptical Restricted Three Body Problem*
ETM	*Equitime targeting method*
FETBP	*Full Ephemeris Three Body Problem*
GMAT	*General Mission Analysis Tool*
IDR	*Instituto Universitario "Ignacio Da Riva"*
IFCA	*Instituto de Física de Cantabria*
MUSE	*Máster Universitario en Sistemas Espaciales*
OTM	*Optimized targeting method*
TBD	*To be done*
UPM	*Universidad Politécnica de Madrid*
WIP	*Work in progress*

1. Introduction

Mubody is an astrodynamics open-source Python library focused on the libration points [1]. Such points result from the equilibrium of the gravitational forces between two massive bodies, e.g., the Sun and Earth. The library is mainly intended for the generation of orbits in these regions, which is not a straightforward process, specially if perturbations are taken into account [2,3].

The interest in these regions has increased in the recent years, with the consequent increment in the scientific research activity focused on this topic on multiple fields as orbit dynamics, trajectory control, spacecraft formations and navigation [4,5]. One of the most common destinations for libration point missions is the L2 point of the Sun-Earth system, which presents ideal conditions for deep space observation due to its stable thermal environment and its distance from near Earth perturbations. The most recent example is the James Webb Space Telescope mission, which successfully deployed in its target Halo orbit [6] in January 2022. Nevertheless, other libration points have been and will be destination of many other missions: the L1 point of Sun-Earth system has been used for several space weather control missions [7,8], the L2 from Earth-Moon was selected by China to place a communication relay satellite for their mission to the dark side of the Moon [9] and the L1 from the same system will be the destination for the future Gateway mission of NASA [10].

Within this scientific topic, the Instituto Universitario "Ignacio Da Riva" from Universidad Politécnica de Madrid (IDR/UPM) participated along the Instituto de Física de Cantabria (IFCA) on a research project of a calibration satellite for CMB telescopes located in L2 [11,12,13]. Mubody originated from this project and started as a script developed by a master student to compute the nominal orbits for the calibration satellite and the telescope. The script was expanded progressively as part of a PhD, motivated by the need of performing mission analysis in libration point regions, until becoming an open-source library with multiple functionalities and oriented to be used and improved by students.

Since its creation, Mubody (its icon is shown in Figure 1) has proven to be an excellent academic tool for both enhancing the library itself and using its results for further studies (collision risk, thermal analysis, formation flight control, etc). As a result, the tool has rapidly evolved, building onto the knowledge and experience that the students gather while working on their academic projects (bachelor's degree dissertations, master theses, subjects, internships). The participation on the library development provides students with experience in orbital mechanics, software design, version control and it compels them to ensure that their work can be readily used by others as it is properly documented.

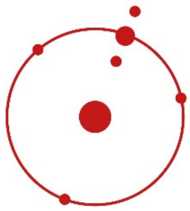

Figure 1. Mubody icon

This paper presents an overview of the library current structure, models and its main capabilities (Section 2), followed by a description of the student involvement (Section 3), and the discussion of the experience results

(Section 4). Finally, the conclusions of this work are presented.

2. Mubody library

Mubody is an acronym for multi-body dynamics, which refers to the dynamics of the gravitational environment created by two or more massive bodies. The library focuses on the three-body problem, which studies the motion of three bodies under their mutual gravitational fields. When there are no restrictions in terms of the bodies masses and initial conditions, it is called the general three body problem. Such problem does not present a closed solution as the two-body problem does. In fact, in most cases the solution is chaotic. Diverse simplifying assumptions lead to interesting cases. The most known are the so-called restricted three body problems [14], where the mass of one of the bodies is negligible when compared to the other two, which are called primaries. Thus, the motion of the primaries is not affected by the third body, and it can be considered as a two-body problem. In the CRTBP the primaries have circular orbits.

The equations of the CRTBP model present 5 equilibrium points, the so-called Lagrange point or libration points, whose locations are shown in Figure 2. The collinear points (L1, L2 and L3) are unstable and if not controlled, any orbit around them will end up scaping from the libration point region and entering an orbit around one of the primaries. Conversely, the equilateral points (L4 and L5) are stable.

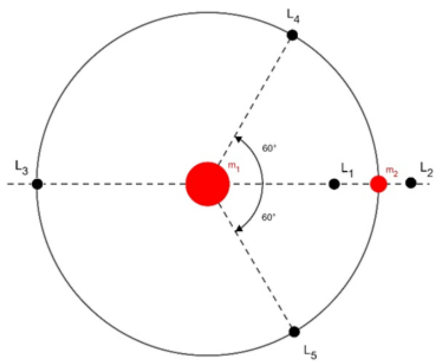

Figure 2. Location of the 5 libration points

The CRTBP model contains many types of different orbits which revolve around the libration points, called libration point orbits (LPO), and they are usually classified into periodic orbits and quasi-periodic orbits. As the CRTBP has not analytical solution, the orbits must be calculated by combining successive approximations with differential correction methods.

The origin of Mubody is in 2018, as a single Matlab script to generate Lissajous orbits (a type of quasiperiodic orbit) in L2 point of the system Sun-Earth. The script contained the analytic solutions for this type of orbits that the linearized equations of the CRTBP model provides [2]. As the project in which it was being used progressed, the script expanded incorporating new functionalities as orbit control and orbit refinement algorithms [15].

Such enhancements were also made by students from both bachelor's degree and masters. All these features accumulated in the same script, which could only analyse one case at the same time.

With the start of a PhD focused on mission analysis of flight formations in L2, it was decided to create the Mubody library as such, switching to Python, establishing a version control through Git [16] and opening a repository in GitLab [17] under a MIT license. These actions were intended to:

- Create a research tool to perform detailed orbital design and analysis.
- Make the tool accessible to others, allowing to reproduce the research results without requiring a paid licence.
- Facilitate the participation of several people in the project at the same time.

With this new approach, the development of the library became faster and easier, implementing an object-oriented structure, following official Python code recommendations, and benefiting from the active Python community online.

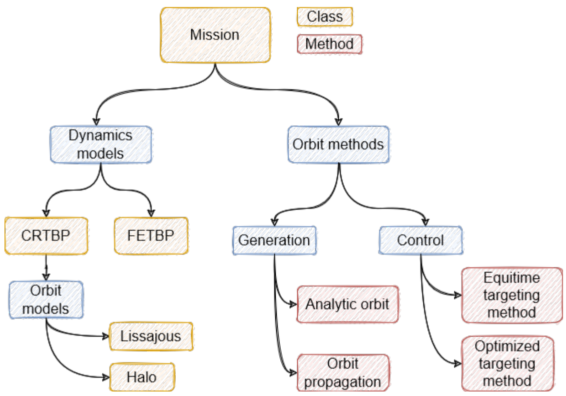

Figure 3: Mubody code diagram

The core of Mubody is the top-level object called *Mission,* where all the data (constants, celestial bodies ephemeris, orbit trajectory, physics models, etc) and methods (generating orbits, refine orbits, plotting, etc) are stored and from which they can be called by the user. The library allows to generate a reference orbit (Lissajous/Halo) using the analytic solution from the linearized CRTBP equations. Such orbit is unstable and direct propagation from any point along it will end up diverging. Thus, it can be controlled (computing the maneuvers required to keep the satellite in such orbit) o refined (reducing the *Δv* required in the control maneuvers). The refinement can be performed using the CRTBP model or the FETBP model. In the Figure 3, a scheme of Mubody structure is shown.

2.1. CRTBP

The study of this problem is simplified by using a synodic reference frame and normalizing the equations of motion. The synodic reference system is centred in the primaries barycenter, with the X-axis passing through the primaries and oriented to the least massive, and the XY-plane coincides with the primaries orbital plane.

Under these considerations, the equations of motion are:

$$\ddot{x} - 2\dot{y} = \frac{\partial U}{\partial x} \qquad (1)$$

$$\ddot{y} + 2\dot{x} = \frac{\partial U}{\partial y} \qquad (2)$$

$$\ddot{z} = \frac{\partial U}{\partial z} \qquad (3)$$

where *U* is a pseudo-potential function defined as:

$$U = \frac{1}{2}(x^2 + y^2) + \frac{1-\mu}{\rho_1} + \frac{\mu}{\rho_2} \qquad (4)$$

and $\mu = m_2/(m_1+m_2)$, the mass ratio between the primaries, which must not be mistaken with the standard gravitational parameter. ρ_1 and ρ_2 are the distances from the primaries to the third body.

If the Eqs.1-3 are linearized, analytic expression for Lissajous and Halo orbits can be found [15,18]. In Figure 4, an example of a family of Halo orbits for Earth-Moon L2 obtained with Mubody is shown.

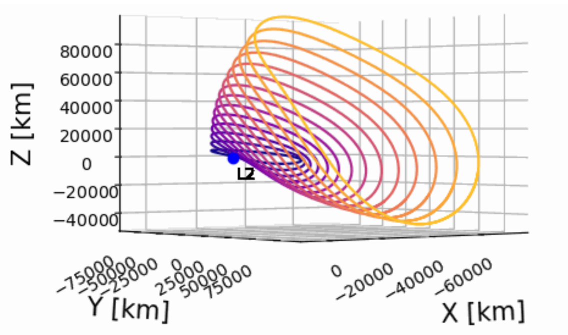

Figure 4. Family of Halo orbits in L2 from Earth-Moon system generated with Mubody

2.2. FETBP

In this model, the motion equation is directly the gravity law, expressed in the EME2000 coordinate system:

$$\ddot{\boldsymbol{r}} = -\frac{Gm_1\boldsymbol{r}_1}{|\boldsymbol{r}_1|^3} - \frac{Gm_2\boldsymbol{r}_2}{|\boldsymbol{r}_2|^3} - \sum_{n}^{i=1}\frac{Gm_i\boldsymbol{r}_i}{|\boldsymbol{r}_i|^3} \qquad (5)$$

where $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ are the position vector from the primaries to the third body and $\boldsymbol{r}_i$ and m_i the position vector to the third body and mass of each of the celestial bodies considered as perturbations.

2.3. Orbit control and refinement

Currently, Mubody implements one method for orbit control, ETM, and a method to refine the orbit, called OTM, both from [15]. An example of application is shown in Figure 5.

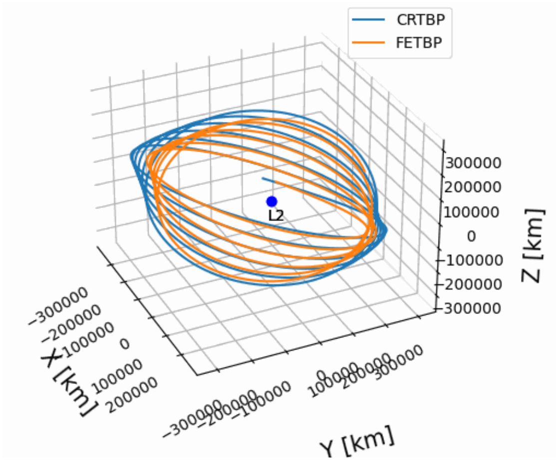

Figure 5. Comparison of refined Lissajous orbit in CRTBP and FETBP

2.4. Summary of capabilities

In Table 1, a summary of the present and planned capabilities of Mubody is shown.

Table 1. Mubody capabilities status

Function	Implemented
N-body propagation	Yes
Halo orbits (CRTPB/FETBP)	Yes
Lissajous orbits (CRTBP/FETBP)	Yes
Sun/any planet/Moon as primaries	Yes
Solar wind perturbation	WIP
Formations	TBD
Transferences to Earth/Moon L2	WIP
Documentation/Examples	Yes
Basic plotting	Yes

Currently, Mubody allows direct propagation of an orbit under the influence of several bodies gravity. By default, all Solar System planets, the Sun, and the Moon are available for this operation as well as to be used as primaries.

3. Students involvement

The capabilities/functionalities of the library have been developed motivated by three factors: one, the engineering projects handled by the IDR/UPM, second, the research performed as part of one of the authors PhD, third, the educational activities in which the library has been used. Although different, these three branches of activities are connected. The engineering projects constitute the source of the questions that the PhD research intends to answer. As these activities are developed within an academic environment at the university, they interact with bachelor and master students through their final dissertations, and cases of study, through which work cases are proposed to the students, with a limited scope, allowing them to participate in a real engineering and research activity as an integrated activity of they academic curriculum [19].

The proposed projects are normally focused on incorporating a new functionality to the library and then use such functionality, together with the rest of the library, to analyse or study a given aspect of a mission. The students are provided with basic bibliography of the topic, which they use as a starting point for a more extensive bibliography research. They are given some basic issues to solve so they familiarize with the library structure, Python language and Git use. Then, they are asked to elaborate a proposal of how they would implement the new functionality.

This approach requires certain degree of independent work by the student, but weekly follow-up and doubts resolution facilitates progress and avoids stalling in minor issues. After implementation, the inclusion of testing and documentation is required. Besides the mandatory dissertation or report, their contribution in the library must be documented, tested, and used in some example cases. Their work will be also included in the repository, with an indication to the used version of Mubody, so their work can be freely used and reproduced, even after the library keeps on developing and changing.

In Figure 6, a scheme is shown of how the Git version control is used to incorporate the changes of a new feature while other contributions are made to the library. This allows to parallelize the library development and avoid the risk of causing a failure on projects using Mubody.

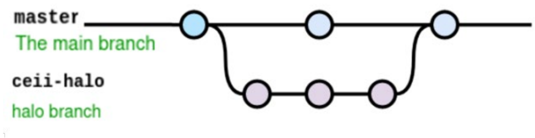

Figure 6. Scheme of Git version control

4. Discussion

The numerical propagation of Mubody has been validated against GMAT, an open-source mission analysis software from NASA. This validation will be automatized in the future so it can be run in each new version of the library.

The educational experience has produced positive results. It is a hands-on project, in an astrodynamics area different from what it is usually taught in aerospace related bachelor and masters syllabus. Students can contribute to something that outlast them and will be used by others. The library has been developed much further than it would have without student collaboration.

The main disadvantage of this approach is that normally students lack experience with version control and object-oriented programming, with the consequent learning curve. Ultimately, this disadvantage is easily overcome by considering an initial period of learning and taking it into account when setting the goals for the project.

Thanks to projects proposed each year as case of study in the MUSE master taught by IDR/UPM, there are multiple opportunities to keep developing the library, with enhancing-oriented projects o with projects focused on libration points that require orbital data that Mubody can provide.

The participation is open to anyone who wants to collaborate, improving the library or using it, specially for students who want to use it in any type of academic work.

5. Conclusions

The development of the library has increased the IDR/UPM know-how in astrodynamics, software development and libration point mission analysis.

Such knowledge has been built in collaboration with bachelor, masters, and PhD students, allowing them to acquire real experience in engineering and research.

All this work is open-source and can be accessed and used freely, which makes research more transparent and facilitates its reproducibility.

The development of the library will continue, focused on orbit design, transference to libration points and formation analysis.

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