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Ballistic landing design on binary asteroids: The AIM case study

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Abstract

The close-proximity exploration of small celestial bodies of our Solar System is the current frontier of space exploration. Trajectory design and exploitation of the natural dynamics around such bodies represents a very challenging astrodynamics problem, due to their weak and highly chaotic gravitational environment. The paper discusses design solutions for the ballistic landing of a small and passive probe, released to land on the smaller of a binary asteroid couple. The work is focused on the Asteroid Impact Mission (AIM) case study, although the methods and analyses presented are general and applicable to any binary asteroid scenario. The binary system is modeled using a shape-based three-body problem and three-body solutions are investigated within the Didymos binary system. Manifold dynamics near libration points associated to the asteroid three-body system are exploited to find low-energy and high-success landing trajectories. The validity of implemented approach and solutions found are discussed and results in terms of success rate and landing dispersion are shown.
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Keywords: Landing; Binary asteroid; Shape model; Didymos; AIM; MASCOT-2

1. Introduction

Due to the large accessibility of the Near Earth Asteroid (NEA) population to spacecraft, rendezvous missions to small celestial bodies of our Solar System are the current frontier of space exploration. Motivated by a great scientific interest and invaluable technological demonstration opportunities, the close-proximity exploration of asteroids and comets is among the latest challenges of modern astrodynamics. Due to their peculiar and irregular mass distribution, the gravity field around such celestial bodies is characterized by an extremely nonlinear and chaotic dynamical behavior.

Among the small body population, binary asteroid systems are of great interest since 1993, when the first natural satellite of an asteroid was discovered. At that time the Galileo spacecraft imaged the asteroid moon Dactyl while performing a flyby near its bigger companion 243 Ida (Belton et al., 1994). In the last few decades, many multiple asteroid systems were discovered and it is currently estimated that about 16% of NEA are binaries (Margot et al., 2002; Merline et al., 2002). The study of binary asteroids can be very interesting under many points of view. These kinds of systems possess peculiar properties that make them good candidates for scientific and technological studies. The binary asteroid environment is the ideal place to study gravitational dynamics, to enhance the understanding of how celestial bodies in the Solar System were formed and how they evolve. More in detail, they offer the unique opportunity to determine precisely asteroid masses and densities: nowadays, mass and density are accurately known only for a few tens of small body objects. In case of binary systems, the mass of the asteroids can be accurately computed after the orbit of the satellite object is measured (Bottke et al., 2002). Binary systems represent

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an ideal place for technology demonstration missions, as a test bench for In-Orbit-Demonstrations (IOD) experiments. For these many reasons, the study of the dynamical environment near an asteroid pair is an extremely relevant topic for future missions design.

The paper discusses the design options for a ballistic landing on the secondary of Didymos binary system, with explicit reference to the Asteroid Impact Mission (AIM) (Ferrari et al., 2016a; Cheng et al., 2015) case study. The mission analysis strategy is outlined and taylored to the peculiar dynamics and requirements related to the AIM mission. Relevant design parameters are identified and their effect on the ballistic landing design is discussed. Expected landing results and proposed mission analysis design solution are also presented. The target is the near-Earth binary asteroid 65803 Didymos (Scheirich and Pravec, 2009). In the following, the primary asteroid is informally called Didymain, while its small companion is called Didymoon.

The mission scenario considers a small lander, named MASCOT-2, to be released on Didymoon's surface, to perform the Moonlet Engineering eXperiment (MEX) that will demonstrate the ballistic landing and operations of a miniaturized asteroid lander on a binary system. MASCOT-2, a very small (about 13 kg) and completely passive probe, is named after MASCOT (Mobile Asteroid Surface sCOuT), the lander on board the Hayabusa-2 mission (Tsuchiyama et al., 2011; Ulamec et al., 2014). The problem of landing a space probe on such celestial bodies is nowadays being studied for the first time and the related research field is very young. The Rosetta mission (Taylor et al., 2015) highlighted the challenges of designing close proximity trajectories and landing a probe on the surface of an extremely irregular body such as comet 67P/Churyumov-Gerasimenko (Sierks et al., 2015), whose shape and mass distribution were completely unknown and unexpected during the mission design phase. In that case, the Philae lander (Biele and Ulamec, 2008) release was challenged by the highly perturbed dynamical environment in the proximity of the comet and by its very low and irregular gravity field. In analogy to the Rosetta mission, the AIM case study entails the release of a small and passive probe that will reach the surface of a largely unknown object after a purely ballistic descent. MASCOT-2 lander does not feature any mechanism to anchor to the surface of the asteroid, which makes the landing design even more challenging. Moreover, Didymos system's gravity field is expected to be weaker, with an escape velocity from Didymoon's surface of few cm/s, since the asteroids are estimated to be nearly two (Didymain) and four (Didymoon) orders of magnitude less massive than comet 67P/Churyumov-Gerasimenko. In addition, the presence of two gravitational attractors makes the dynamics in the close proximity of the couple highly unstable and chaotic. The accurate knowledge of the dynamics driving the motion of a body in the vicinity of such a binary system is then a key point for the success of the mission, to correctly operate scientific payloads and to effectively land the probe on the asteroid.

An effective strategy for MASCOT-2 release is proposed here. The increased complexity of having two small bodies as gravity source is used here as a potential opportunity to be exploited in the design process, through the use of three-body modeling techniques. The AIM/MASCOT-2 scenario is presented in the following paragraphs as a case study. However, the applied methodology is representative for any asteroid/small body scenario.

2. Dynamics

The dynamics of MASCOT-2 in the proximity of the binary asteroid system are modeled using the Restricted Three-Body Problem (R3BP), with shape-based models to reproduce the gravity field generated by the two asteroids.

2.1. Asteroid models

Few strategies are usually adopted to model the gravity field about asteroids. Classic methods consider harmonic expansion of gravitational potential (Kaula, 1966) to model the irregularities of a simple Keplerian field. Shape-based methods are used to model the asteroid as objects with specific shapes, such as homogeneous ellipsoids (Scheeres, 1994) or polyhedra (Werner and Scheeres, 1997; Scheeres et al., 1998): in this case their distribution of mass is not spherical and the gravity field in its proximity is computed accordingly. Other methods use a number of masses (mascon models) to reproduce the mass distribution of the body. The mascon method was first developed to explain the anomalies of the Moon's gravity field by Muller and Sjogren (1968). The inclusion of concentrations of mass in the nearly spherical mass distribution of the Moon helped in the development of a highly accurate lunar gravity model. A similar technique is used to reproduce the gravity field of asteroids (Colagrossi et al., 2016; Ferrari et al., 2017; Geissler et al., 1996). The applicability of each method depends on the information available on the body's mass distribution and on the level of accuracy required by the application. Typically, each model fits a specific class of asteroids and application range. In general, the determination of mass and bulk density of small body is a very difficult task (Hilton, 2002) and very little is known about their internal mass distribution.

According to the latest observations of Didymos system, information on the shape of the asteroids are partially available. A face-vertex shape model of Didymain is available,[1] while Didymoon's shape is estimated to be an elongated tri-axial ellipsoid. The implementation is based on the methods proposed by Werner and Scheeres (1997)

[1] The Didymain shape model is used in the frame of ESA's AIM contract, however it is still unpublished (courtesy of L. Benner and S. Naidu).

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