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Potential trajectory design for a lunar CubeSat impactor deployed from a HEPO using only a small separation delta-V

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Abstract

Potential impact trajectories for a lunar CubeSat impactor mission are designed and analyzed under the condition that only a small delta-V from the mechanical separation mechanism from the mother-ship is available. The orbit of the mother-ship from which the CubeSat is deployed is assumed to be a Highly Elliptical Polar Orbit (HEPO) around the Moon, and candidate peri- and aposelene altitudes are investigated. The resultant trajectory parameters for the CubeSat impactor are also analyzed. The impact footprint dispersion characteristics are roughly estimated considering the uncertainties that may arise at the moment of CubeSat deployment. As a result, a set of HEPO shapes that can successfully impact the lunar surface using a deployment delta-V of only 2 m/s is discovered. The delta-V required to separate the CubeSat, which is up to tens of m/s, can be greatly reduced depending on the geometry between the Earth and the orientation of the HEPO of the mother-ship at the moment of deployment. The dispersion characteristics of the impact footprint are more sensitive to the uncertainties in the velocity than in the position at the time of separation. From the point of view of the current proposed trajectory design, an uncertainty of less than several tens of cm/s in the velocity should be guaranteed for successful impact within a radius of several tens of kilometers of the target.

Keywords: Lunar Exploration; CubeSat; Impactor; Trajectory design

1. Introduction

CubeSats have largely served as education platforms since they were first invented in 1999. However, CubeSat technology has advanced rapidly, and several projects are underway to perform CubeSat-based lunar and planetary exploration. Most planetary exploration to date has been achieved through remote sensing from orbiters or through surface exploration by landers. However, such methods are expensive and risky, and the science data gathered from the near surface can be limited (Klesh and Castillo-Rogez, 2012). Therefore, CubeSat payload planetary missions are enthusiastically suggested not only for the Moon but also for Mars, Europa, and other deep space exploration missions. The Jet Propulsion Laboratory (JPL) is preparing several CubeSat planetary science missions. For example, Mars Cube One (MarCO), the twin CubeSats expected to launch in 2018 (or later), will be the first CubeSats flown into deep space (Asmar and Matousek, 2014). In 2017, the Interplanetary NanoSpacecraft Pathfinder In Relevant Environment (INSPIRE) CubeSat will be launched to demonstrate the fundamental capabilities of deep space CubeSats, including command, data handling, telecommunication and navigation (JPL, 2016a). Recently, the National Aeronautics and Space Administration's (NASA) Advanced Exploration Systems (AES) selected the Lunar

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Flashlight and Near Earth Asteroid Scout (NEAScout) missions for new upcoming missions to be launched in 2018 for CubeSat-based planetary exploration (JPL, 2016b).

Since 1992, Korea has been continuously operating more than ten Earth-orbiting satellites. It is now beginning to expand its interests to planetary missions. The Korean space program plans on launching a lunar orbiter and lander and on exploring explore Mars, asteroids, and deep space in the future. For the first step, the Korea Pathfinder Lunar Orbiter (KPLO), an experimental lunar orbiter that will orbit the Moon at approximately 100 km for one year, is scheduled for launch in approximately 2019 with international collaboration. The Korean lunar science committee has been working to select the main scientific objectives for the lunar orbiter mission, and one of the candidates is to fly a CubeSat impactor to explore lunar magnetic anomalies and associated albedo features, known as swirls (Lee et al., 2014). The lunar magnetic fields have already been measured by both NASA's Lunar Prospector and the Japan Aerospace Exploration Agency's (JAXA) KAGUYA mission. However, the measurement data are not sufficient to completely characterize the magnetic anomaly regions because they were obtained at high altitudes (>20 km) (Garrick-Bethell et al., 2013). Similar to how most previous lunar orbiters have ended their missions, a lunar orbiter could be crashed into a target area to take measurements at low altitudes. However, such an impact not only is expensive but also has limited launch accessibility. Therefore, a new idea is to use a CubeSat carrying a magnetometer as a payload, and impacting the target region has already been discussed (Garrick-Bethell et al., 2013). Two major lunar transfer scenarios are proposed to deliver the CubeSat impactor. The first transfer scenario is to establish a Geostationary Transfer Orbit (GTO) with the launch vehicle; then, the Planetary Hitch Hiker (PHH) spacecraft concept is used to deliver the CubeSat payload impactor to the Moon. In the second scenario, the CubeSat impactor utilizes its own minimal ion propulsion system to spiral out to the Moon after being placed into geostationary orbit (GEO) as a part of a geostationary spacecraft's payload. However, these two mission scenarios have several challenging aspects to overcome, for example, longer flight times to reach lunar orbit (expected to be more than 100 days), tolerating large amounts of radiation exposure even though the mission starts from GEO, and, most importantly, establishing a shallow impact angle (<10°) during the impact phase to meet the science objectives. This last factor is a more critical factor if a mother-ship is not used (Garrick-Bethell et al., 2013). Note that the impact angle in the current study is defined with reference to the Moon's surface to ensure that measurements occur over a long enough horizontal distance to address the mission objectives. Considering the above, Song et al. (2015a) proposed the concept of flying a lunar CubeSat impactor as one of the scientific payloads on a lunar orbiter, i.e., the mother-ship, and analyzing the CubeSat impact trajectory characteristics as a function of its deployment conditions. In Song et al.'s (2015a) work, a mother-ship is assumed to travel in a circular polar orbit at an altitude of 100 km from the Moon. In addition, all necessary parameters required in the early design phase, including the CubeSat flight time to reach the lunar surface, the impact velocity, the cross range distance, and the associated impact angles, were analyzed using simplified system dynamics. Song et al. (2015a) found that very shallow impact angles (<10°) can be achieved with the proposed CubeSat impactor scenarios, which is a critical requirement to meet the science objectives. However, the minimum required divert delta-V magnitude to impact the CubeSat was found to be quite large, and thus, the necessity for an onboard CubeSat propulsion system was declared. Later, Song et al. (2015b) extended their simulations to higher altitude ranges with the CubeSat impactor still released from circular orbits around the Moon. Despite the higher altitude of the CubeSat deployment, additional delta-V support from an onboard CubeSat propulsion system is necessary to meet the mission objectives. Thus, thruster burn time and fuel mass were analyzed in Song et al.'s (2015b) work by adapting miniaturized commercial onboard thrusters developed for CubeSat applications.

Although deploying a CubeSat impactor from a mother-ship in a circular orbit satisfies the critical mission requirement discussed above, loading a propulsion system on the CubeSat impactor may increase not only the complexity of the CubeSat system design but also its operational procedure, which may reduce the overall mission success. Moreover, the CubeSat scientific payload capacity must be maximized. To maximize the payload capacity, the required delta-V must be minimized to conserve the onboard fuel. To minimize the delta-V required to deploy the CubeSat, one solution would be to release the CubeSat from a Highly Elliptical Polar Orbit (HEPO) around the Moon; this type of orbit can be established during the mother-ship's lunar capture phase. Therefore, the current work is focused on analyzing lunar CubeSat impactor deployment opportunities from HEPOs around the Moon when only the small separation delta-V induced by the mechanical separation mechanism from the mother-ship is available. First, the sizes and shapes (especially the peri- and aposelene altitudes) of candidate HEPOs that have the potential for CubeSat impact are investigated, and the related trajectory parameters of the CubeSat impactor are analyzed. In addition, the corresponding dispersion characteristics of the impact footprint, considering the many uncertainties that may arise at the moment of CubeSat separation, are analyzed to roughly estimate the system design requirements. The remainder of this manuscript is organized as follows. The formulation of the CubeSat impact problem, especially the mathematical models for the equations of motion and the impact parameter derivation, are explained in detail in Section 2. The numerical implications and the assumptions adopted in