Hayabusa 2 extension plan: Asteroid selection and trajectory design

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ARTICLE INFO

Keywords:
Low-thrust trajectory design
Asteroid selection
Hayabusa 2
Asteroid flyby

ABSTRACT

The Hayabusa 2 mission is targeted to explore the asteroid (162173) 1999 JU3 and return surface as well as subsurface samples through a novel impactor. Upon its return, at the end of 2020, the spacecraft will release the capsule for Earth re-entry and drift away from the planet. Based on the current mission profile, the spacecraft is expected to retain 30 kg of xenon propellant for trajectory maneuvers after the capsule is released. This remaining fuel can be used to extend the mission and improve its scientific return by exploring a new target. Work herein outlines an extension plan for Hayabusa 2, detailing the target selection process and its subsequent trajectory design. Due to final Earth escape trajectory, considering the excess velocity and orbital geometry, the only available extension option is an asteroid flyby. One of the most important trajectory characteristics is to maximize the spacecraft’s optical detection capabilities. As a result the asteroid 2001 WR5 is identified as the most promising target candidate. The resulting trajectory uses all the available xenon with 100% duty cycle. Furthermore, the extension lasts for 932 days and offers 1.57 days of optical navigation time for a flyby on June 27, 2023.

1. Introduction

After the success of Hayabusa [1], JAXA planned and launched its second asteroid sample return mission, Hayabusa 2, on 3 of December 2014 [2]. The mission targets the C-type asteroid (162173) 1999 JU3, also known as Ryugu, to study the origin and evolution of the solar system as well as the building block materials for life. Hayabusa 2 mission was launched in a near 1:1 resonant orbit with Earth, which allowed it to perform a gravity assist one year later changing the spacecraft orbital inclination. The spacecraft uses \( \mu \) 20 ion engines to maneuver in deep space and rendezvous with the asteroid (1999 JU3).

One of the most important characteristics of the extension trajectory is the optical navigation time that the spacecraft has prior to the target encounter. The Hayabusa 2 spacecraft has a high definition camera used for close proximity operations on (162173) 1999 JU3. This camera is capable of detailed imaging with a small observation angle and, due to this, the camera does not perform well for distance targeting. Its field of view is narrow, and it cannot identify distant objects - apparent visual magnitude detectable by the spacecraft camera is low. In the case of rendezvous with Ryugu, the arrival velocity is low and trajectory correction maneuvers near the encounter can be easily made. During the target arrival on the extension phase, however, the high definition camera has to be used for the encounter operations. Because of its poor performance for distant targets, sufficient time needs to be allocated for target identification and trajectory correction maneuvers. Therefore, in order to maximize the trajectory arrival robustness and the overall mission reliability, the objective for the trajectory design is to maximize the optical navigation time upon target arrival.

This work uses a combination of linear dynamics, optimal control as well as reachability theory to find potential targets and design a flyby trajectory [4] taking into account the full asteroid database [5]. The method for asteroid selection is based on a step process that progressively eliminates targets that are impossible to reach. It also provides a good estimation of the trajectory states and thrust profile for the final non-linear optimization. Once the initial selection is made, asteroid and...
orbit characteristics - such as final mass, Sun-asteroid-spacecraft solar phase angle (SPV), H magnitude, asteroid spectrum type, time of flight and optical navigation time - are taken into account to further narrow the selection [6]. Finally, a global non-linear direct method optimization tool coupled with monotonic basing hopping [7,8] is used to calculate a trajectory with the maximum optical navigation time in the target arrival. A set of possible targets and their associated trajectories are defined through this method for the Hayabusa 2 extension mission. A final application of these results will depend on a successful Earth return and a proper execution of the pre-entry maneuvers.

After this introduction, the paper provides a general overview of the Hayabusa 2 mission in section 2. The details of the mission extension analysis as well as mission component segmentation are described in section 3. In section 4, the spacecraft dynamics and equations for calculating the optical navigation time are detailed. Sections 5 and 6 outline the theories and results achieved in the target selection and trajectory design, respectively. Finally, section 7 presents the conclusions of this work.

2. The Hayabusa 2 mission

Asteroid Explorer Hayabusa 2 is a successor of the previous Hayabusa mission, also known as MUSES-C. The first Hayabusa was successful in operating several new technologies and returning to Earth samples of the Apollo asteroid (25143) 1998 $SF_6$, also known as Itokawa [10], in June 2010. Together with establishing a new navigation method using solar electric propulsion for asteroid sample return, the mission was the first to bring to Earth asteroid samples that help to elucidate the origin of the solar system. Similar to its predecessor, Hayabusa 2 targets the exploration of the C-type asteroid (162173) 1999 $JU_3$, leveraging the experience acquired from the Hayabusa mission. C-type asteroids are primordial bodies expected to be rich in organic or hydrated minerals [9]. Basic elements forming the Earth’s minerals and seawater as well as the building blocks of life are believed to have originated in the primitive solar nebula of the early solar system.

Hayabusa 2 builds on the electric propelled round-trip exploration technology developed by the Hayabusa mission, but also develops new technology to construct the basis for future deep space exploration. Spacecraft configuration is very similar to its predecessor. Key modifications include the flattened double antenna, previously single parabolic, and the new plastic-based impactor. The impactor creates an artificial crater that exposes subsurface material, which is less weathered by the space environment and heat. With this, both surface and sub-surface samples can be acquired in a single sample mission. Hayabusa 2 was launched on 3 of December, 2014 and is predicted to arrive at the C-type asteroid in mid 2018. Science on the asteroid will last 1.5 years with the spacecraft asteroid departure expected at the end of 2019 and Earth return in December 7, 2020 [11].

3. Mission extension design method

The extension mission starts once the spacecraft escapes from the Earth after the capsule is released, Fig. 1. Earth escape conditions are fixed based on the capsule release requirements, which is a priority at the Earth encounter. Entry conditions targeting is made through chemical burns hours before the atmospheric entry. The resulting ballistic trajectory after the escape can be seen in Fig. 2, which is propagated for 5 years.

Once the chemical burns are finished, the spacecraft’s maneuverability capacity is very limited by the amount of xenon remaining, roughly 30 kg. However, the remaining xenon can still be used by the electric propulsion system to change the trajectory enough to fly by a new target, improving the mission’s science return. The mission extension options become limited: given the orbit geometry and propellant available, both rendezvous and planetary encounters are impossible. Only a flyby mission can be realized within the spacecraft and orbit capabilities. Furthermore, asteroids and comets are the only suitable body for this extension due to their abundance. Priority is given to find a reasonable flyby trajectory that can be achieved with the available xenon while maximizing optical navigation time. As mentioned previously, Hayabusa 2 has a high definition camera for proximity operations.

The design process is then divided into two parts: target selection and trajectory design. First, the target selection makes use of the full Minor

![Fig. 1. Mission extension roadmap.](image1)

![Fig. 2. Hayabusa 2 final Earth escape trajectory.](image2)
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