frontiers | Frontiers in Space Technologies

TYPE Editorial
PUBLISHED 22 March 2023
DOI 10.3389/frspt.2023.1173593

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Space Robotics, a section of the journal Frontiers in Space Technologies

RECEIVED 24 February 2023
ACCEPTED 07 March 2023
PUBLISHED 22 March 2023

CITATION
Soldini S, Trigo-Rodriguez JM, Hirabayashi M, Moussi A and Tsuda Y (2023), Editorial: Advancing robotic exploration of asteroids and comets: A threat, an opportunity, or both? *Front. Space Technol.* 4:1173593. doi: 10.3389/frspt.2023.1173593

Editorial: Advancing robotic exploration of asteroids and comets: A threat, an opportunity, or both?

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KEYWORDS

asteroids, comets, small-body mission design, close-proximity mission operations, asteroid resources

Editorial on the Research Topic
Advancing robotic exploration of asteroids and comets: A threat, an opportunity, or both?

Asteroids and comets are pristine leftovers from the formation of our Solar System 4.6 billion years ago. They are rich in key elements that support life and exploring them will expand our understanding of the Solar System's formation and life on Earth. The gravitational forces of large planets and collisions with other asteroids and comets alter their orbits, which are also affected by other non-gravitational forces. Thus, following many deflections, they may occasionally intersect Earth's orbit and could pose a threat to our planet. While asteroids and comets might pose a threat, they are also rich in valuable resources and may represent an opportunity for future space economy and for supporting human spaceflight. In recent years, advancements in robotic spacecraft have allowed a further understanding of their formation in some cases by returning samples.

Since 2019, many robotic spacecraft have been sent to visit asteroids. JAXA's Hayabusa2 mission (Hirabayashi and Tsuda, 2022) returned Ryugu samples in December 2020 and will arrive at asteroid 1998 KY26 in 2031 (Hirabayashi et al., 2021). NASA's OSIRIS-REx (Lauretta et al., 2017) will return Bennu samples in September 2023. In October 2021, NASA's Lucy mission (Levison et al., 2021) was successfully launched, and is planned to visit one asteroid from the main asteroid belt and seven of Jupiter's trojan asteroids. While NASA's DART (Rivkin et al., 2021), the first planetary defense mission to the Didymos binary system, was launched in November 2021 and successfully impacted Dimorphos in September 2022. ESA's Hera mission (Michel et al., 2022) will follow DART with a launch expected for 2024 while JAXA is planning a sample and return mission to Phobos with the launch of MMX in 2024 (Nakamura et al., 2021). Finally, NASA's Psyche mission (Oh et al., 2019) will visit the first metal asteroid in 2026. The aim of this Research Topic is to focus on the technological advancement in robotic spacecraft for future missions to minor celestial bodies. This includes the use of mobile rovers, landers (i.e., Hayabusa2 mission), and CubeSats (i.e., DART and Hera). Particular focus is given to trajectory design methods (e.g., orbiting, hovering, and landing), mission operations (e.g., touchdown and artificial impact), and the use of autonomy.

This Research Topic *Advancing robotic exploration of Asteroids and Comets: a threat, an opportunity, or both?* aims to present the latest advancements in robotic exploration of asteroids and comets with a particular interest in or focus on the use of landers, mobile rovers, and CubeSats. The scope of this Research Topic is to provide the latest guidance and navigation techniques for autonomous exploration including trajectory design, orbit determination, instruments, and operations around minor bodies tackling the problem of operating a spacecraft around the weak gravity field of minor celestial bodies.

Close proximity operations on the surface of small celestial objects are a great challenge due to their weak gravitational field. The uneven terrain of asteroids causes local gravity anomalies which depend on the topography of the target object. Noeker and Karatekin tackle this problem by proposing a novel gravimetry method called "wedge-pentahedra method" for topographic correction for (near-) surface gravimetric measurements, which is applied in the case of Phobos (Mars' moon). The presented approach was verified and suggested for future landing operations.

The advantages of landing on a minor body have been successfully highlighted by both the JAXA's Hayabusa and Hayabusa2 missions, with the possibility to compare *in-situ* observations of the asteroid surface with laboratory experiments of samples returned to Earth. This represents an important benchmark to prevent contamination of the samples. Maturilli et al. is dedicated to linking *in-situ* and ground laboratory spectroscopy for the Ryugu asteroid, visited by the Hayabusa2 spacecraft. Hayabusa2 was equipped with CNES' MASCOT lander (Ho et al., 2021) which has performed *in-situ* spectroscopy of Ryugu. The article describes the procedure and validation of the comparison test in preparation of the analysis of Ryugu samples returned back to Earth. The article is a methodology paper that validates the process to be used for the analysis of the real samples. The results presented here are compared with the Mukundpura meteorite, a recently fallen meteorite that is considered as one of the best Ryugu analogs in the meteorite collection.

While surface samples provide important information on asteroids' composition and origin, sub-surface material can provide pristine information on its property, as asteroidal surfaces are subjected to environmental changes. A way to evaluate the strength of an asteroid and access its sub-surface sample is to perform an artificial impact experiment. This was the case in the Hayabusa2's spacecraft with the Small Carry-on Impactor (SCI) operation that released a copper bullet of 2 kg at 2 km/s. The OSIRIS-REx spacecraft sampled the surface of Bennu with a robotic arm called TAG. The effect of the robotic arm has caused a small sub-surface material to be revealed. The TAG operation has provided key information on the strength of the target as the top of the robotic arm sank inside the surface. Most recently, NASA has deliberately impacted the DART spacecraft (570 kg) at a speed of 6.6 km/s on Dimorphos (the moonlet of the Didymos binary asteroid) as the first in a space full-scale planetary defense test which has successfully proven the kinetic impact deflection technique for rubble-pile asteroids. Moreover, the impact is providing further information on their strength, formation, structure, and composition. Impact operations or low-speed surface interaction cause the lift-off of ejecta material that could compromise the functionality of the spacecraft.

Soldini et al. evaluated a novel and fast methodology to determine the probability of the ejecta damaging the spacecraft after impact. The article focuses on the post Hayabusa2's SCI operations. To determine the impact velocity of particles on the spacecraft, a two-point boundary value problem between the spacecraft location and SCI impact location was formulated. The approach is fast and can be used during mission operations, allowing a trade off in area-to-mass ratio of particles to be tested. The method is independent from the condition of the terrain but, to evaluate the number of particles that are actually likely to have impacted the spacecraft, the power-law distribution of ejecta particle size along the crater was used. The target thickness equation was used to determine the threshold of damage of an Al plate.

Traditional asteroid missions require a dedicated launch vehicle to reach their final target asteroid. Takei et al. proposes a novel approach to perform interplanetary Earth departure trajectory from the low Earth orbit (LEO) at more affordable launch costs. The core idea proposed in this article is to achieve launch speed flexibility from LEO by proposing two distinct maneuvers: the one-revolution Earth free-return orbit (1rEFRO) and the consequent Earth gravity assist (EGA). These allow for separating the velocity increment and direction adjustment. While planetary free-return and EGAs are common in interplanetary missions, this article provides a comprehensive study on the flexibility, economic efficiency, and arbitrariness of the sequence (1rEFRO + EGA) originating from LEO. This study revealed that LEO has both flexibility and economic efficiency as a parking orbit for deep space missions by adopting the 1rEFRO + EGA sequence. Based on these results, the study of a standardized deep space orbital transportation architecture starting from LEO, which is expected to significantly reduce the unit cost per launch weight in the future, can be accelerated.

After Philae's experience on 67P/Churyumov-Gerasimenko comet as a first lander test in the framework of the Rosetta (ESA) mission (Accomazzo et al., 2017), there is no doubt that landing and exploring the surface of a comet is one of the biggest challenges in Solar System exploration. The last article in this Research Topic investigates a new mission concept to visit a comet. Marschall et al. propose a mission called ORIGO that is planned to deliver a lander to the surface of a cometary nucleus where it will characterize the first 5 m of the subsurface. The proposed mission plan is to deploy remote sensing instruments and payload into a borehole to study the physico-chemical structure of ancient, unmodified material. The main objectives of the ORIGO mission are to understand if cometesimals are formed by distinct building blocks, determine if refractory and volatile materials came together during planetesimal growth, and examine if the building blocks of planetesimals all formed in the vicinity of each other, or if there was significant mixing of material within the protoplanetary disk. The article proposes an outline and mission configuration of ORIGO.

Author contributions

SS and JT-R organized and wrote the manuscript. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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