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Path planning and control for asteroid ejecta collection after a kinetic impact

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Abstract

In recent years, missions such as JAXA's Hayabusa2 and NASA's OSIRIS-Rex have visited Near Earth Asteroids, explored their environments, and collected samples from these primordial Solar System bodies. Their physical composition is largely unknown and challenging to predict from ground observations. That is why sample collection from such bodies is crucial for the future exploration of the Solar System. Hayabusa2 and OSIRIS-Rex used two different yet similar sampling collection methods. In both cases, a touch-and-go scenario was exploited and, while for OSIRIS-Rex the surface of Bennu was directly sampled, Hayabusa2 first hit asteroid Ryugu with a small kinetic impactor to create a crater. One of the most challenging aspects of such missions is to collect and sample asteroids material by means of an on-ground collection, involving landing (or touchdown) and probing the asteroid's soil. In some cases, the probing may be difficult because of a challenging dynamical environment or dangerous terrain features. In this context, starting from the heritage of the Hayabusa2 mission, we propose a novel mission concept in which the spacecraft hits the asteroid using a small kinetic impactor. Such an small impact will generate a plume of ejecta, similar to the one produced by the impact of the Small Carry-on Impactor (SCI) of Hayabusa2 on asteroid Ryugu. However, differently from Hayabusa2, we envision the possibility of collecting the fragments of the plume directly in orbit; therefore, without landing or touch down. Starting from the dynamical evolution of the fragments, this work studies what are the possible collection regions around the asteroid based on their availability and concentration. To ensure the maximum number of samples is collected, with the desired area-to-mass characteristics, a path planning optimisation is performed, where the waypoints of the path are selected as the time-varying location of the maxima of the particle fluxes around the asteroid. Finally, we analyse the necessary control history required to follow the optimal trajectory using a Sliding Mode controller. Constraints in terms of illuminations, safety for the spacecraft and communication with the Earth are considered in the trajectory design. The work then discusses the feasibility of the mission and a preliminary concept of operations.

Keywords: asteroid missions, asteroid samples, sample collection, trajectory design, guidance and control

Acronyms/Abbreviations

This section is not numbered. Define acronyms and abbreviations that are not standard in this section. Such acronyms and abbreviations that are unavoidable in the abstract must be defined at their first mention there. Ensure consistency of abbreviations throughout the article. Always use the full title followed by the acronym (abbreviation) to be used, e.g., reusable suborbital launch vehicle (RSLV), International Space Station (ISS).

1. Introduction

Space exploration missions to asteroids have always drawn the attention of the scientific and engineering community given the challenges they pose and the possibility they present to further our knowledge of the Solar System. Asteroids carry fundamental information on the evolution of our Solar System. They are rich in valuable resources such as metals, silicates, and water, which could be exploited through future asteroid mining missions, and enable long-duration mission self-sustaining. The physical composition of asteroids remains, in most cases, poorly understood with the means available from ground. Space missions can be exploited to improve the knowledge by collecting and studying samples of asteroids. Several missions have visited asteroids and other small bodies; however, only few have orbited, landed, or impacted on them. Examples are JAXA missions Hayabusa and Hayabusa2, ESA Rosetta, and NASA OSIRIS-REx and DART. One of the most challenging aspects of such missions is to collect and sample asteroids material by means of an on-ground collection, involving landing (or touchdown) and mining.

In this context, starting from the heritage of the Hayabusa2 mission [5][6][7], we propose a novel mission concept in which the spacecraft hits the asteroid using a small kinetic impactor. Such an impact will generate a plume of ejecta, like the one produced by the impact of the Small Carry-on Impactor (SCI) of Hayabusa2 on asteroid Ryugu. However, differently from Hayabusa2, we envision the possibility of collecting the fragments of the plume directly in orbit; therefore, without landing or touch down. Such a mission scenario could expand the opportunity of future sample collection missions with additional collection mechanisms. In addition, it could enable sample collection even when the environmental conditions are challenging or even extreme. For example, in the case of fast rotating asteroids, where landing or touch down would be extremely challenging, or for asteroids with extreme terrain features that could prevent the spacecraft from approaching the surface.

In this work, we analyse a scenario in which the spacecraft shoots at the asteroid a kinetic impactor, like the one of mission Hayabusa2. The plume generated by such an impactor is composed of billions of small fragments that will follow predictable trajectory [11][12]. By designing a trajectory that "follows" the plume of fragments, the spacecraft can collect a large number of samples when equipped with a suitable collection mechanism. The objective of this work is to devise a method to design the path the spacecraft should follow to maximise the sample collection, based on the characteristics of the impact. Once the trajectory for collection has been identified, a sliding mode controller is used to control the spacecraft along the desired trajectory.

2. Methodology

The methodology followed for the path planning and control of trajectory aimed at the collection of fragments orbiting around asteroids is composed of two main parts. The first part (Section 2.1) is dedicated to identifying the path the spacecraft should follow to maximise the collection of the orbiting samples. The objective of this procedure is to generate a sequence of *waypoints* through which the spacecraft should pass a specified time. These waypoints will make up the path the spacecraft needs to follow for the collection mission. The second part (Section 2.2) instead consists of the sliding mode controller, which is used to find the thrust sequence that the spacecraft needs to perform to follow the path specified by the waypoints.

2.1 Path planning procedure

The path planning procedure consists in identifying the location of waypoints around the asteroid through which the spacecraft should pass at specified instants in time. Because the objective of the path planning is to create a trajectory that would maximise the collection, we make use of information concerning the flux of particles around the asteroid.

To do so, we follow the procedure described in [1][4]. In summary, the procedure consists in simulating the impact of a small kinetic impactor on the asteroid surface via a weighted Monte Carlo sampling [3]. The generated samples are then propagated in time and their position is saved at predefined snapshots. After the propagation, we construct a spherical grid around the asteroid and compute the density and flux of the particles in each one of the bins of the spherical grid and at each snapshot (Figure 1). In this way we obtain the evolution in time of the distribution of fragments fluxes around the asteroid.

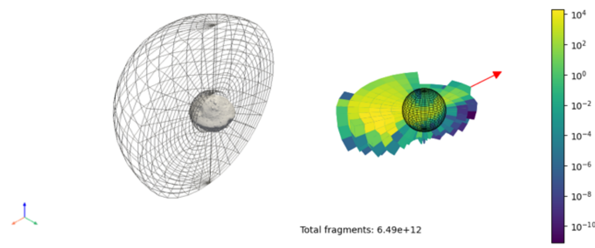

Figure 1: Cut-out of the spherical grid around the asteroid (left). Example of the distribution of particle density computed on the spherical grid (right).

It is easy to realise that passing through the areas where the flux is the highest allow collecting the greater number of samples. Therefore, for each snapshot, we select as waypoint the centre of the spherical bin corresponding to the greatest flux, such that:

$$\forall\, s \in S, \{r_w, \alpha_w, \delta_w\} \in G \mid \Phi_s(r_w, \alpha_w, \delta_w) = \max \Phi_s(r, \alpha, \delta) \quad (1)$$

where S is the set of snapshots, G represent the set of coordinates of the centroids of the spherical grid around the asteroid, Φ_s is the set of fluxes on the spherical grid G corresponding to the snapshot s, and (r_w, α_w, δ_w) are the spherical coordinates of the waypoint at the considered snapshot.

However, if the waypoints are selected only following this criterion, the result may be a trajectory with an erratic distribution of waypoints that would be difficult to follow for the control algorithm and would be operationally infeasible for the spacecraft. Therefore, additional constraints have been included for the waypoints' selection:

- Avoid points too close to the asteroid's surface.
- Avoid points whose connecting line intersects the asteroid (to avoid crushing onto the asteroid during the manoeuvre between two waypoints)
- Limit the maximum distance from the asteroid.

- Limit the minimum time delta between two waypoints.
- Starting from a waypoint, remove all the waypoints that cannot be reached by the spacecraft, given its propulsion capabilities and the time available between two snapshots. In this case, a simplified straight motion with only thrust acceleration is considered:

  $$d_{max} = \eta \cdot a_t \cdot dt$$

  where a_t is the thrust acceleration in N, dt is the time interval between two consecutive snapshots, and η is a scaling coefficient.
- Do not generate a new waypoint if the relative change in fluxes at the new waypoints is smaller than a user-specified threshold.

Following the principle of maximising the particle flux and considering the previously listed constraints, at each snapshot a waypoint is selected, based on the position of the previous waypoint. We then procced to the next waypoint and repeat the procedure until the last snapshot has been processed. Figure 2 shows an example of selected waypoints.

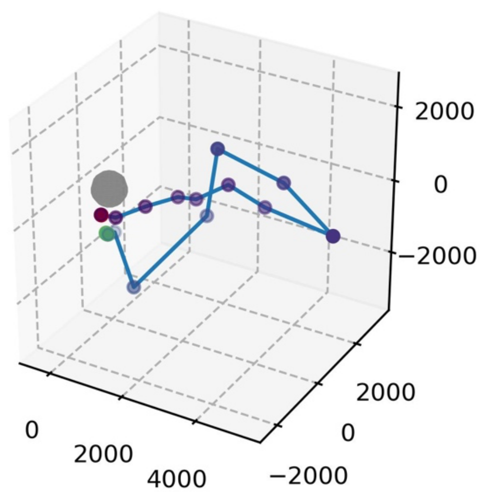

Figure 2: Example of waypoints selected with the outlined procedure.

2.3 Computation of total number of impacts

Let us consider a spacecraft of cross-section A; at a certain instant in time, the spacecraft will occupy a position in space around the asteroid. This position will fall inside one of the spherical bins in which we have subdivided the space around the asteroid. When inside this bin, we consider that the spacecraft is affected by the fragments of density $\rho(r, \alpha, \delta)$, moving with average speed $\boldsymbol{v}(r, \alpha, \delta)$. Considering the spacecraft speed we can compute the impact rate of particles on the spacecraft, $\dot{\eta}_{sc}$, as follows:

$$\dot{\eta}_{sc}(r, \alpha, \delta) = \rho(r, \alpha, \delta) \cdot |(\boldsymbol{v}(r, \alpha, \delta) - \boldsymbol{v}_{sc})| \cdot A \quad (2)$$

where $\boldsymbol{v}_{sc}$ is the velocity of the spacecraft in the bin. In time, the spacecraft will move through different spherical bins. We can compute the estimated number of impacts on the spacecraft with the following approximation:

$$N_{imp} \cong \sum_{t=1}^{N_T} \dot{\eta}_{sc}^{t}(r_t, \alpha_t, \delta_t) \cdot \Delta T_t \quad (3)$$

where N_T is the number of waypoints in which the spacecraft trajectory is discretised. At this stage of development of the methodology, we consider that the spacecraft at time t is influenced by the fragments inside the bin it is occupying until the next point along its trajectory, t+1, for a time ΔT_t.

By exploiting the discretised nature of the simplified flux representation of the ejecta cloud, we can estimate the number of impacts on the spacecraft surface. With this methodology, we can thus estimate the collection capability of the spacecraft instrument as the spacecraft follows a specific trajectory around the asteroid.

2.4 Sliding-mode control

The way the spacecraft moves around the asteroid influences its capabilities to collect the fragments. Once we have selected the waypoints as in Section 2.1, we need the control the spacecraft to pass through them and exploit the high fluxes for collection. To do so, we have decided to use a sliding-mode controller [9][10]. Such a control is stable and reliable and has been used for the design of missions such as OSIRIS-Rex. In the following, we briefly describe the sliding-mode control adopted in this work. For further details, the user is referred to [9].

Consider a dynamical system of the form:

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{f}(\boldsymbol{x}, t) + \boldsymbol{b}(\boldsymbol{x}, t)\boldsymbol{u} \\ \boldsymbol{s} &= \boldsymbol{s}(\boldsymbol{x}, t) \end{aligned} \quad (4)$$

where $\boldsymbol{x}$ is the state, $\boldsymbol{u}$ is the controller, and $\boldsymbol{s}$ is the sliding function. The goal of the control is to make the sliding function to vanish in a finite time and keep it zero indefinitely. In our case, the sliding function is defined as:

$$\boldsymbol{s} = \boldsymbol{r} - \boldsymbol{r_d} \quad (5)$$

where $\boldsymbol{r}$ is the position of the spacecraft in time and $\boldsymbol{r}_d$ is the desired position. It can be shown that the sliding-mode control acceleration can be written in the form:

$$\boldsymbol{a}_c = -\boldsymbol{A}\,\mathrm{sign}\left[\dot{\boldsymbol{s}} + \boldsymbol{B}\,|\boldsymbol{s}|^{\frac{1}{2}}\,\mathrm{sign}(\boldsymbol{s})\right] \quad (6)$$

where $\boldsymbol{A}$ is a diagonal matrix, whose elements are the magnitude of the thrust acceleration and B can be chosen such that:

$$\boldsymbol{A} - \boldsymbol{D} \geq \frac{1}{2}\boldsymbol{B}^2 \quad (7)$$

where $\boldsymbol{D}$ is a diagonal matrix that represents the upper bound of the total uncertain dynamical accelerations acting on the spacecraft.

2.5 Dynamical model

The dynamical model used in this work for both the propagation and the sliding-mode control is the Photo-gravitational Hill Problem [2]. The equations of motion are expressed in non-dimensional form in a synodic reference frame centred in the asteroid. The x-axis is along the Sun-asteroid direction, pointing outwards, the z-axis is along the direction of the angular momentum of the asteroid orbit, and the y-axis completes the right-hand system.

$$\begin{cases} \ddot{x} - 2\dot{y} = -\dfrac{x}{r^3} + 3x + \beta \\ \ddot{y} + 2\dot{x} = -\dfrac{y}{r^3} \\ \ddot{z} = -\dfrac{z}{r^3} - z \end{cases} \quad (8)$$

where x, y, and z are the non-dimensional particle positions with respect to the centre of the asteroid in the synodic frame, and $r = \sqrt{x^2 + y^2 + z^2}$ is the particle's distance from the centre of the asteroid. The lightness parameter β can be expressed as follows [2][1]:

$$\beta = \frac{P_0}{c}\frac{AU^2}{\mu^{\frac{1}{3}}\mu_{\mathrm{Sun}}^{2/3}}\frac{3(1 + c_{\mathrm{R}})}{2\rho_{\mathrm{p}} d_{\mathrm{p}}} \quad (9)$$

where $P_0 = 1367$ W/m^2 is the solar flux at 1 AU, c is the speed of light, AU is the astronomical unit, μ_{Sun} and μ_a are the gravitational parameter of the Sun and the asteroid, respectively, ρ_p is the particle density, d_p the particle diameter, and C_r the reflectivity coefficient (here considered equal to the albedo of the asteroid). Eclipses are considered using a cylindrical shadow model via a modified lightness parameter, β^*:

$$\beta^* = \begin{cases} \beta & \text{if } x \leq 0 \\ \beta \cdot f(\sigma) & \text{otherwise} \end{cases} \quad (10)$$

where $f(\sigma) = (1 + e^{-s\cdot\sigma})^{-1}$ is a sigmoid function with steepness parameter s, which, in this work is equal to 8. The variable $\sigma = r_x - R_a$, with $\mathrm{r_x} = \sqrt{\mathrm{y}^2 + \mathrm{z}^2}$ distance to the x-axis.

4. Results

The methodologies outlined in Section 2 are applied to the test case of a kinetic impactor onto asteroid Ryugu. The characteristics of the asteroid are summarised in Table 1.

Table 1: Characteristics of asteroid Ryugu [5].

Quantity	Symbol	Value
Mean radius (m)	R_a	440
Bulk density (g/cm3)	ρ	1.19
Albedo	C_r	0.037
Rotational period (h)	T_r	7.627

The impact on Ryugu's surface is analogous to the one carried out by Hayabusa2, and its characteristics are summarised in Table 2. The impact is equatorial and at a right ascension of 270 degrees as measured from the x-axis of the synodic frame (frame rotating with the asteroid around the Sun, with x-axis pointing from the Sun to the centre of the asteroid).

Table 2: Impactor properties [5][8].

Quantity	Symbol	Value
Speed (km/s)	U	2
Radius (m)	a	0.075
Density (g/cm^3)	δ	2.7

For the generation of the ejecta samples, Ryugu's terrain is modelled as a sand-like material with very low equivalent strength (~0 Pa). This is in accordance with the findings in [8], which showed a crater formation in the gravity regime for the SCI experiment of Hayabusa2. A total of 500 000 samples have been generated and used to create the particles' fluxes at snapshots in time. The total propagation time has been set to 24 hours and a total of 48 snapshots, one each 30 minutes, have been generated.

To generate the waypoints, we set a minimum distance from the asteroid's surface of at least 300 m (to avoid possible collisions with the asteroid), and a maximum distance from the asteroid of 6 km. In addition, the coefficient η for the maximum pruning distance is set to 0.5. Finally, the next waypoint can only be selected among locations with at least 50% of the flux of the starting waypoint. If no such locations are available, the spacecraft will remain at the original waypoint. This ensures that the spacecraft does not use fuel to move into a region where the potential for collecting particles is too low. The results of the path planning procedure is a sequence of waypoints as shown in Figure 3

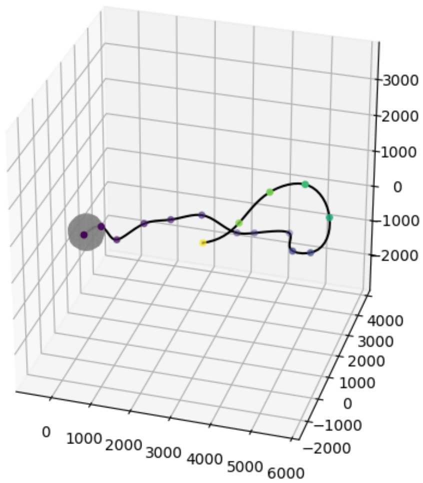

Figure 3: Collection path and waypoints generated by the procedure outlined in Section 2 for the case of a small-kinetic impactor on asteroid Ryugu.

Once the path has been planned, we need to find the control history that will allow the spacecraft to follow the trajectory. To do so, we adopt the sliding-mode controller described in Section 2.4. For this test case, the characteristics of the spacecraft are summarised in Table 3. For the sliding- mode controller, the upper bound of the uncertain dynamical acceleration has been set to $D_i = 10^{-5}$, where D_i are the components of the diagonal of the matrix $\boldsymbol{D}$ (see Eq. (7)). The components of the diagonal of matrix $\boldsymbol{A}$ are instead equal to 0.03 m/s^2. The sliding mode control is applied in sequence to move from one waypoint to the next. The resulting trajectory connecting the previously found waypoints is shown in Figure 4.

Table 3: Characteristics of the spacecraft.

Quantity	Symbol	Value
Mass (kg)	$m_{S/C}$	600
Cross-section (m2)	A	30
Thrust (N)	T	20
Specific impulse (s)	Isp	290

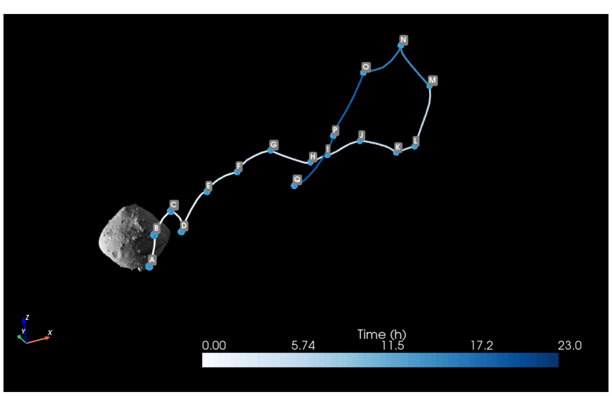

Figure 4: Trajectory connecting the path defined by the waypoints using the sliding-mode control.

From the trajectory we can observe that the spacecraft starts close to the asteroid in the region of the impact point. Subsequently, it moves towards the antisolar direction, where most of the fragments generated by the impact starts to move because of the solar radiation pressure. One it reaches the furthest point allowed by the constraints (6 km), it starts to come back towards the asteroid, where there are still particles orbiting.

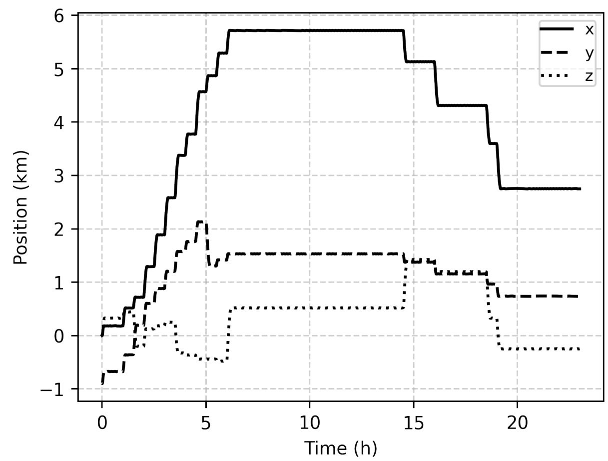

Figure 5: Evolution in time of the coordinates of the satellite around the asteroid.

From Figure 5 is possible to observe that some of the waypoints are maintained for longer than one snapshot and, in these cases, the spacecraft hovers in that position. For the waypoints that do not need hovering, a convergence radius of 50 m has been used so that the spacecraft does not stop completely and keeps moving towards the next waypoint.

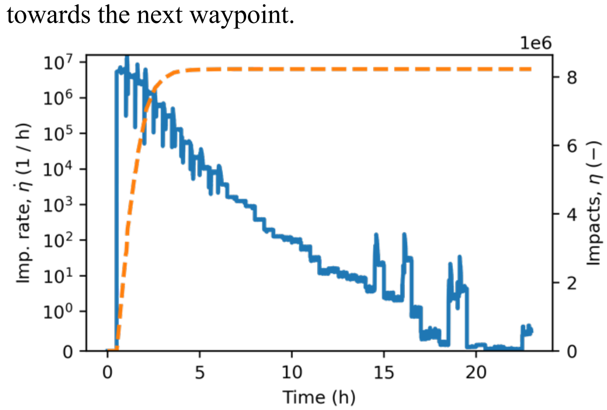

Figure 6: Impact rate and cumulative impacts on a 1 m^2 surface belonging to the spacecraft as a function of time.

Finally, Figure 6 shows the impact rate and the cumulative number of impacts in time for a 1 m^2 surface on the spacecraft. Such a surface is used as a reference to simulate the size of a sample collection mechanism. Firstly, we can notice that for this scenario, it would be possible to collect about 8 million particles generated by the kinetic impactor. We also notice, as expected, that the highest impact rates are in the first hours after the impact: this is when the spacecraft is close to the impact point and the fragments are less spread out. Therefore, their density and flux are higher. The impact rate then drops quickly (logarithmically) as the particles spread, and the density lowers the further away we move from the asteroid. It is also interesting to observe the oscillating behaviour of the impact rate, particularly at the beginning. This is due to the changes of velocity of the spacecraft during the manoeuvres. Using a sliding-mode control, the spacecraft first accelerates and the coasts towards the waypoint. This sequence of acceleration and coasting is what is also causing the flux of particles seen by the spacecraft to oscillate and, with it, the impact rate.

6. Conclusion and discussion

In this work, we have presented a methodology to design and control trajectories around small bodies such as asteroids to perform sample collection in-orbit. These study stems from the interest in investigating alternative ways of sample collection that part from the classical touch-down and landing cases. To do so, a mission concept is investigated that generates a plume of ejecta by launching a high-speed small kinetic impactor onto the asteroid. Simulating the trajectories of these samples, it is possible to predict where the cloud will move in time and thus estimate the flux of particles around the asteroid. We have used this information to design a trajectory that would maximise the collection of the generated samples. The trajectory design is based on the identification of waypoints through which the spacecraft path should pass. In addition, we have developed a sliding-mode control to allow the spacecraft to move between the waypoints. We have proved, using a mission around asteroid Ryugu, that the presented methodology is able to generate a path for the spacecraft that allows the collection of a large number of samples. Furthermore, we have demonstrated that the designed trajectory is feasible and that can be maintained using a simple yet effective sliding-mode control.

Acknowledgements

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