NEXT GENERATION OF MASCOT NANO-LANDERS FOR THE MULTIPLE NEO RENDEZVOUS MISSION: A Self-transferring Lander For The 'Sousveillance' Of NEOs For Space Exploration, Planetary Defence Or Resource Utilisation

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Abstract

This is an exciting time for Near-Earth Object (NEO) Exploration as we get closer to finding answers to many important questions on how the Solar System was formed, how life arrived on Earth and how the vastly unknown Small Solar System Bodies (SSSBs) behave. In the next three years we will see the return of asteroid samples by the HAYABUSA2 and the OSIRIS-REx missions and the launch of the NEA SCOUT, PSYCHE, LUCY, DART and HERA missions. Yet the NEA classifications are not exhaustive and each new asteroid provides its unique challenges. Thus, an on-site study via nano-landers has multi-fold advantages as they can provide a detailed scientific analysis and can lay the foundation for In-situ Resource Utilisation (ISRU) missions by the selection and geo-spatial mapping of the target site and by the testing of the relevant technology demonstration. Until now nano-landers have been deployed from an altitude of 40-100 meters. This paper aims to exploit the high vantage point of small spacecraft technology to study micro-gravity bodies by proposing a self-transferring, highly integrated nano-lander that can be deployed at ten to hundred-fold higher altitudes than before. It is a successor of MASCOT – the DLR-CNES nano-lander aboard HAYABUSA2 that successfully operated on (162173) Ryugu in 2018.

An exciting prospect for future MASCOTs is a Multiple-NEO Rendezvous (MNR) mission by a Solar-Sailing spacecraft. A previous GOSSAMER based study proves the feasibility of a ten-year mission that could deploy five MASCOTs to five asteroids in hundred days. This paper goes one step further and equips the nano-landers with minimalistic self-transfer GNC and Propulsion systems thereby enhancing the multiple target mission returns while conforming to the nano-spacecraft's system design constraints. Additionally, a software-in-the-loop mission design and a Monte Carlo sensitivity analysis have been done to prove its capability to land on the moon of binary asteroid systems that are critical target bodies for the development of planetary defence technology. The proposed MASCOT-variant can have a customised payload for individual target bodies. This system can hence pave way to a new generation of intelligent yet simple landers that can help in all the fields of NEO studies such as reconnaissance missions preceding human exploration or asteroid mining missions. Looking at how many extra miles a self-transfer MASCOT could scout ahead, the mission parameters are outlined for an added in-situ exploration capability which is simultaneously relaxing the requirements on and de-risking the operations of its main spacecraft.

Keywords: Small Spacecraft Technology, MASCOT, GOSSAMER, Multiple-NEO Rendezvous Mission, Self-transferring Nano-lander, Solar Sail

Nomenclature

L_1, L_2 – Lagrange points 1, 2
m_i – mass of components in a binary NEA
r – radius from barycenter
r_i – radius from components in a binary NEA
X_S,Y_S,Z_S – synodic reference frame in PCR3BP
μ – mass ratio of components in a binary NEA

Acronyms/Abbreviations

AIDA – Asteroid Impact & Deflection Assessment
AIM – Asteroid Impact Mission
CMOS – Complementary Metal-Oxide-Semiconductor
CNES – Centre National d'Études Spatiales (National Centre for Space Studies)
CR3BP – Circular Restricted Three Body Problem
DLR – Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre)
FOV – Field Of View
GNC – Guidance, Navigation and Control
IR – Infrared
ISRU – In-Situ Resource Utilisation
MARA – MASCOT Radiometer
MASCAM – MASCOT Camera
MASCOT – Mobile Asteroid Surface SCOuT
MASMAG – MASCOT Magnetometer
MNR – Multiple NEO Rendezvous
NEA – Near-Earth Asteroid
NEO – Near Earth Object
PCR3BP – Planar Circular Restricted Three Body Problem
PHA – Potentially Hazardous Asteroid

SSSB – Small Solar System Body
U – CubeSat size unit of 1 dm³ and 1 kg

1. Introduction

The term sousveillance had been coined by S. Mann for the use of wearable sensors (cameras, Fitbits, etc) for the observation of human activities to counter or assist conventional surveillance from above [1]. This paper draws a parallel of the term sousveillance for the in-situ study by nano-landers in the future missions of NEA in-situ resource utilisation (ISRU), asteroid mining, planetary defence or Solar Science missions. The vantage point of these landers over past nano-landers is its self-transferring capability that will de-risk the main spacecraft and reduce the mission timeline that was earlier needed for the more complex close approach operations.

Current work in space exploration includes many missions to asteroids and other Small Solar System Bodies (SSSBs). The reason for their increasing popularity as target bodies is the high scientific return from a single mission [2, 3, 4]. They provide answers to all the key questions in Planetary Science.

On October 3rd, 2018, at about 3 x 10^8 km from our planet, the Japanese spacecraft, HAYABUSA2 [h], dropped a 10 kg nano-lander called MASCOT [g] on (162173) Ryugu, a potentially hazardous asteroid (PHA) of the rare spectral type, Cg. The shoebox-sized lander then surpassed its expected operational time and worked for two asteroid days or over 17 h for the in-situ data collection and also in support of sample site selection. MASCOT played the key role of de-risking the main spacecraft and providing additional in-situ scientific mission capabilities. However, there has been very little work done on deploying such small spacecraft from a farther distance such that they can navigate semi-autonomously to the target bodies. Such a lander will not only de-scope costly and risky hover or close proximity operations of a large spacecraft at largely unknown micro-gravity bodies but it will be also be useful in other mission scenarios like fly-bys of multiple rendezvous missions.

With this goal in mind this paper presents a novel mission concept that builds on the multiple NEA rendezvous (MNR) mission design [c][i][j] of the DLR Solar Sail project, GOSSAMER [a][b] developed further in the recent years by J. T. Grundmann et al. [2]. The study proposed the deployment of MASCOT nano-landers to each visited asteroid by dropping the passive lander at a close distance of around 50 – 100 m. The contribution of this study is to use an enhanced derivative of MASCOT landers that is self-transferring from a safe deployment distance of 2 km or above. The mission design here hence relies on an 'orbiter' or rather, station-keeping solar sail, GOSSAMER, and a MASCOT-derivative nano-lander for the 'sousveillance' or in-situ observation of each target body visited to help the orbiter like the Fitbits used for supporting modern health monitoring system.

1.1 GOSSAMER – Small Spacecraft Solar Sails for MNR Missions and more

The DLR-ESTEC GOSSAMER Roadmap [f] NEA Science Working Groups' studies [c][d][e] identified Multiple NEA Rendezvous (MNR) as one of the space science missions uniquely feasible with solar sail propulsion. Solar sail exploration is not limited by fuel capacity which implies a low launch mass and volume that can be accommodated in a multiple small satellite space launch system. Thus, a small spacecraft like GOSSAMER can help achieve a high scientific-return, from a low-cost and low-mass small spacecraft mission. The unique MNR mission defined by Grundmann et al. [2] based on trajectory studies by Peloni et al [i][j] provides the opportunity to visit 5 interesting asteroid in 10 years with the GOSSAMER-1 derived solar sails.

An interesting advantage of a low-risk lander with a flexible mission criteria is its usability in case of a change in the target body of the GOSSAMER mission during its cruise phase. Such a scenario can arise as seen in a previous Planetary Defence Conference exercise where a newly discovered PHA, 2011 AG_5, is approached by the GOSSAMER spacecraft by a changed

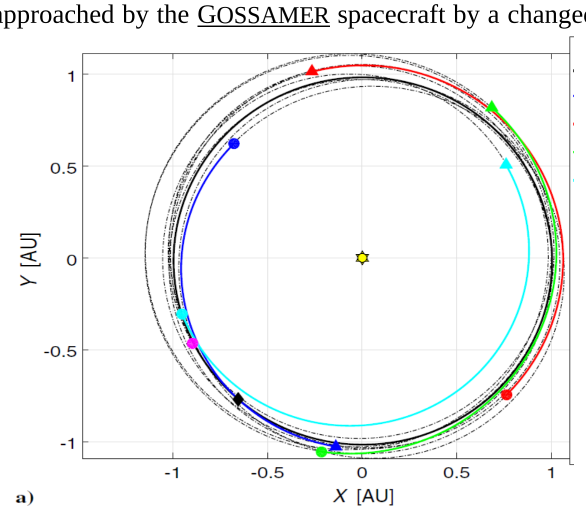

Figure 1 Original mission design of GOSSAMER MNR mission to 5 asteroids in 10 years (adapted from [i][j])

sequence of attitude manoeuvres that allows it to change its fifth asteroid (pink dot in Figure 1) to the given PHA as shown as the outlier pink dot in Figure 2.

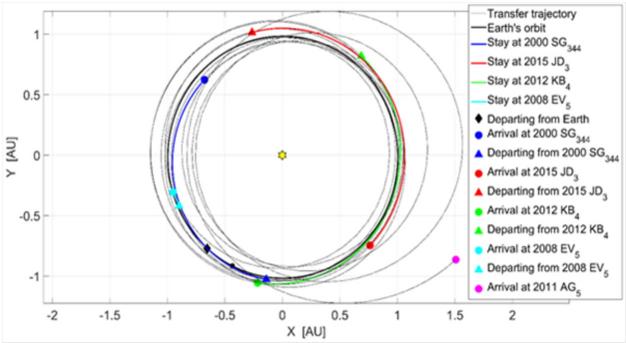

Figure 2 Modified trajectory of GOSSAMER MNR mission to reach a PHA, 2011 AG_5 in 2037 for station keeping until its approach to Earth in Feb 2040 (adapted for [2] from [i][j])

1.2 MASCOT nano-landers

The Mobile Asteroid Surface Scout (MASCOT) shown in Figure 3 is a nano-lander that doesn't have an active Guidance, Navigation and Control (GNC) system except for a self-righting mechanism (an internal swinging mobility arm) [4, 5]. After it had been dropped on the asteroid Ryugu by HAYABUSA2, it bounced on the surface for a couple of hops before settling down. Then it performed a self-righting procedure to re-orient for precise measurements. Later, it relocated on the asteroid by using its internal mobility arm to hop over. MASCOT's unique hopping mobility [6, 7] was designed for the unknown microgravity environment of small bodies and is independent of the topography. This is beneficial compared to a wheeled rover which is dependent on the terrain and is limited by slow translational velocity to prevent a loss of surface contact due to a high angular spin of its wheels relative to the minute force of gravity.

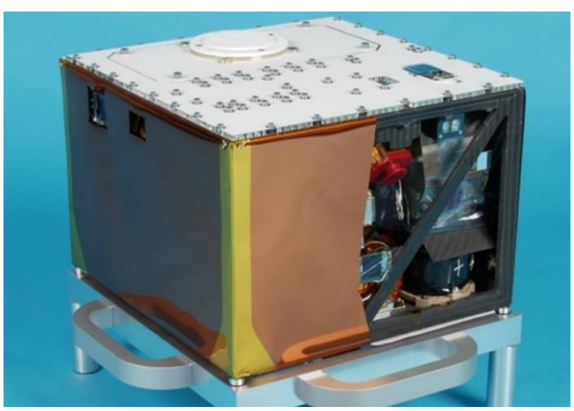

Figure 3 The Flight Model of MASCOT

All the instruments for the in-situ experiments worked successfully and are listed below:

1. MASCAM - A compact wide-angle (*f*/16 aperture) CMOS camera with 72.5^0 diagonal Field of View (FOV) and a spectral range of 400 nm – 870 nm to image the surface of Ryugu.
2. MARA - A multispectral thermal IR Radiometer to study the asteroid's thermal inertia and surface mineralogy in the range of 5 µm – 15.5 µm from six channels with a 30^0 FOV.
3. MicrOmega - A near-IR hyper-spectral microscope provided by CNES to study the surface mineralogy and molecular composition with a 3.2 x 3.2 mm FOV and a spectral range of 0.99 - 3.65 µm. It has been inherited as a scientific payload in ExoMars Rover 2020.
4. MASMAG - A fluxgate magnetometer to measure the 3-axial magnetic field with an accuracy better than 1 nT. It has been used on missions as diverse as BEPICOLOMBO and ROSETTA/PHILAE.

MASCOT is an organically integrated unit with instruments, bus hardware and software, sharing data and utility wherever possible. MASCOT successors are aimed to have similar integrated functioning where there is no fixed demarcation of components based on subsystems so that a simple and compact system can extract multiple tasks from what is available in an 18U space (where 1U is defined as a cubesat of 1 kg mass and 1 dm^3 volume). Thus, with a very high payload-to-mass ratio (> 30%) and a reduced risk of exploring unknown bodies for the main mission, several follow-on studies were conducted for future missions.

MASCOT2 is proposed in the paper by C. Lange et al. [9] with a detailed analysis of a new model of MASCOT with many improvements, from a close-loop control for surface translation with an additional mobility arm for 2D movement, to the addition of new instruments for more science objectives to new navigation systems. This study was done in the context of AIM, the European part of the AIDA mission, now re-scoped and re-designated as HERA that will visit the binary asteroid system of Didymos and its moon, Dimorphos (formerly known informally as Didymoon). This asteroid system and its mission parameters are also taken into account here to simulate the landing of the proposed MASCOT-derivative on Dimorphos.

2. Mission Design for the MASCOT-derivative

The aim of this study is to enable the MASCOT derivative to land on the moon of the Didymos binary asteroid system with the addition of minimal GNC and propulsion systems to cruise from a large distance of around 2 km from the orbiter. The additional systems should ensure that the mass and volume of the lander is as that of a small spacecraft that can be carried by a solar sailing spacecraft.

The chosen landing mechanism is driven by the mission requirements of the main spacecraft. The key factors in the case of landing strategies for micro-gravity bodies are:

1) Spacecraft parameters – Separation velocity; Duration of descent and/or saturation time of reaction wheels; Net errors in position and velocity; Touchdown speed and angle of impact; Coefficient of restitution of impact.
2) Main spacecraft capabilities – Separation mechanism; Delta-V capacity of main mission.
3) Aspects of small target body – Irregular and unknown gravity; Landing site selection; Surface density errors.

It is noteworthy that unlike conventional landers for Mars or Moon, the landing on small bodies is not constrained by high shock loads to instruments but by the small escape velocity of the target. For the stable manifold proposed for ballistic landing by S. Tardivel and D. Scheeres [10] (described in Sub-sec 2.1 below), its failure rate increases proportionally to an increase in the deployment altitude as the approach velocity increases. Hence, active landers are required for farther distances with capabilities to navigate, decelerate and either land in a controlled up-right position or fall passively with a small speed to settle down after a few unpredictable hops. However, no study is found for such small microgravity landers with semi-autonomous control and active propellant system that are below 25 kg.

2.1 Trajectory optimisation by PCR3BP

An attempt is made to utilise the orbital dynamics of a three body system and identify a least-energy path for the lander such that minimal hardware and mass needs to be added to the existing flight model. In the late 1960s, C. Conley [11] and V. Szebehely [12] laid the foundations of Circular Restricted Three Body Problem (CR3BP) for the trajectory designs of the Earth-Moon, Earth-Sun and other three body missions. Here the term 'restricted' means that the two main celestial bodies affect the system dynamics whereas the third object is a point-mass that moves under their influence with no effect of its own. For a preliminary design, landing on the Didymos system is defined as a Planar CR3BP (PCR3BP) with the third object being the MASCOT derivative lander.

The Synodic Reference Frame (X_S,Y_S,Z_S) is used. This is a rotating frame fixed at the barycentre. Here, X_S is directed from Didymos (primary body) to Dimorphos (secondary body), Y_S is along the direction of velocity of Dimorphos and Z_S is along the angular momentum of the binary system (see Figure 4**)**. The reference system is normalised such that the unit distance is the distance between Didymos and Dimorphos, the unit time is the mean motion which is also equal to the rotation rate of the binary and the unit mass is total mass of the binary system.

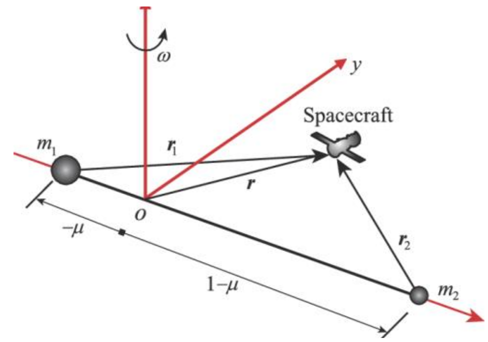

Figure 4 Normalised Synodic Reference Frame Used

C. Conley [11] found optimal transit trajectories and stable manifolds in CR3BP for the transit of a visiting spacecraft. Thus, the Conley criteria can help find the optimal initial state space vector, X, for any start point. The conditions to reach the stable manifold are calculated with the frame's origin shifted to the Lagrange 2, L_2, point. On linearisation of motion near L_2, the state equation is obtained as Eq. 1.

$$\dot{X} = \mathcal{A}X \qquad (1)$$

S. Tardivel and D. Scheeres [10] utilise this equation to extract a low-energy transit manifold at the L_2 point. This stable manifold is unique to the small body binary systems due to their high radius-to-orbit ratio as opposed to the planet-moon systems. The following equations are obtained with variables from the matrix $\mathcal{A}$ in Eq. 1 the optimal deployment conditions – y_0, V_0, θ_0 of the lander for a given initial distance, x_0, from the barycentre with the relation to the position and velocity uncertainties accounted by the variable x_c:

$$x_c = -\frac{\lambda}{a}\sqrt{1+\sigma^2}\Delta V_{error} - \sqrt{\frac{1+b^2\sigma^2}{a^2}}\Delta P_{error} \qquad (2)$$

$$y_0 = \begin{cases} 0, & x_0 < x_c \\ \sigma(x_0 - x_c), & x_0 \geq x_c \end{cases} \qquad (3)$$

$$\theta_0 = \chi = \chi_s + \pi = \arccos\frac{1}{1+\sigma^2} \qquad (4)$$

$$V_0 = \begin{cases} 0, & x_0 < x_c \\ \lambda\sqrt{(1+\sigma^2)}\,(x_0 - x_c), & x_0 \geq x_c \end{cases} \qquad (5)$$

Apart from the gravity of the two bodies the other forces in play consist of the thrust force that is assumed for a constant mass as:

$$\overrightarrow{a_{th}} = \frac{F_{th}}{m_{MSC}} \qquad (6)$$

Thus the final equations of motion for the spacecraft become

$$\ddot{x} = 2\dot{y} - \Omega_x + \vec{a}_{th,x}\,,$$

$$\ddot{y} = -2\dot{x} - \Omega_y + \vec{a}_{th,y} \qquad (7)$$

The above equations have been used for the trajectory design in the subsequent sub-section to find a least-energy transfer of the nano-lander.

2.2 Mission Timeline and Trajectory

To model the system the following assumptions are taken into consideration:

- The time frame for landing is short enough for the binary system to remain fixed in the inertial reference frame.
- The two asteroids rotate in a circular orbit about their barycentre such that the distance between them remains constant.
- The primary bodies are spherical with uniform mass distribution.
- The mean rotation rate of the primary bodies is equal to that of the binary system. Thus, the orientation of both is fixed with respect to each other.
- The third body, the lander in our case, is taken as a point mass that has no influence on the binary system.
- The lander faces the Sun at a constant angle such that its largest surface area is normal to the incident sunlight. (This assumption helps in designing a simple attitude control mission with an ideal placement of photovoltaic cells).

The important physical parameters used to model the Didymos system are given in Table 1. The trajectory thus obtained from the optimal condition equations and the equations of motion as shown in Figure 5 helps outline the design parameters for a novel MASCOT-derivative. Thus if the MASCOT-derivative is deployed by the orbiter with the desired optimal velocity vector and position with respect to the barycentre then it will follow the stable manifold path to reach the secondary asteroid. This lander will only require a single deceleration burn on a close approach during a ballistic landing to reach a low impact speed to get captured by the gravity of the target body (Figure 6).

Table 1. Didymos 1996 GT, Binary asteroid system parameters

Parameters	Binary System	Didymos	Dimorphos
Mass (kg)	5.278 x 10^{11}	5.223 x 10^{11}	4.863 x 10^{9}
Density (g/cm^3)	2.1 ± 0.6		-
Mean Radius (m)	-	385	75
Rotation Period (h)	11.92	2.26	11.92
Binary Asteroid System Parameters			
Mass ratio (μ)		0.0093	
Semi-major axis (m)		1180	
L_1 , L_2 from Dimorphos (m)		70, 85	
Escape Speed (cm/s)		32.4	
Escape Speed at L_1, L_2 (cm/s)		5.11 , 4.57	

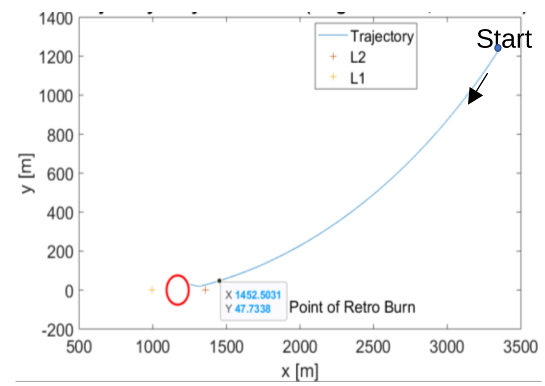

Figure 5 Trajectory of the MASCOT-derivative landing on Dimorphos in the Synodic Frame

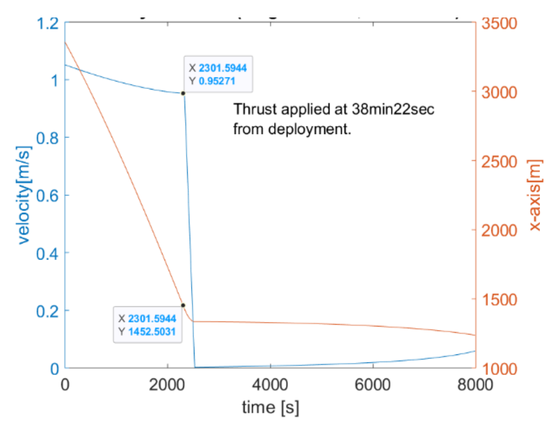

Figure 6 Velocity profile of the MASCOT-derivative for the trajectory shown in Fig. 5

A Monte Carlo sensitivity analysis of the mission shows a high success rate of 97.4% of landing on Dimorphos (Figure 7). In a 1000 runs simulation, 75% cases had an impact speed of around 5 cm/s and 16% cases have an impact speed of < 4 cm/s (Figure 7). In total 98.5% cases have a velocity of < 10 cm/s during touchdown or close approach. Here the net acceptable position and velocity error margins are ±50 m and ±5 cm/s.

Thus this study shows that using the gravitational potential field and a low fuel impulse burn these nano landers can reach complex binary asteroid systems from a distance of 2 km or more. The cases that have a low speed beyond the Lagrange 2 point but do not reach the surface of the target would still remain captured by the binary asteroid system's gravity and orbit around the two bodies. Then a second attempt at landing can be done by

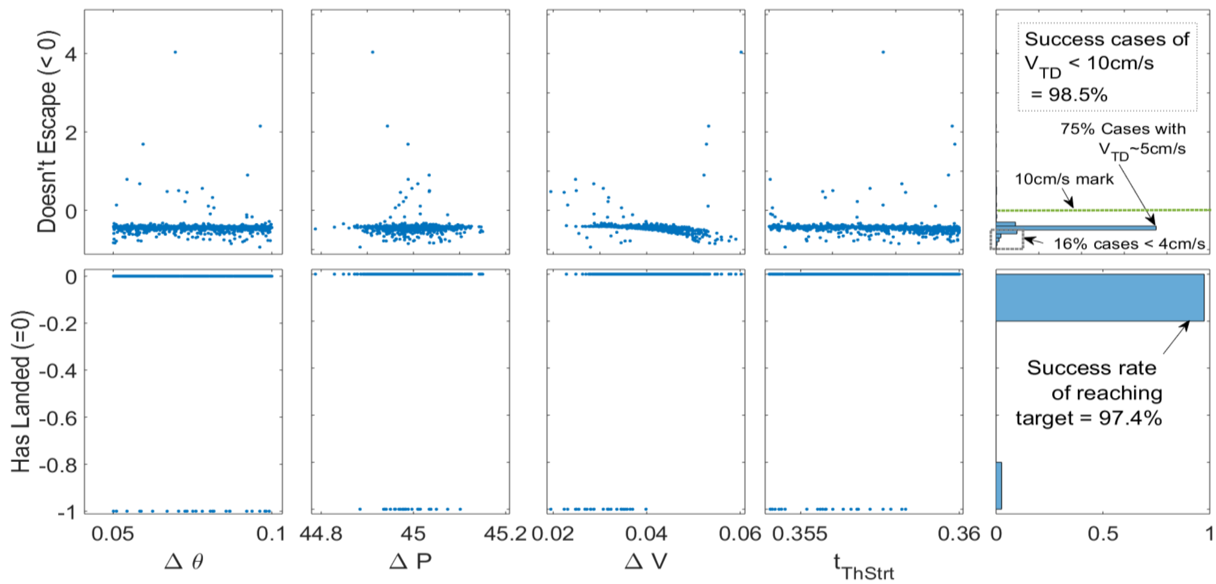

Figure 5 Sensitivity analysis of the proposed mission for varying error margins of attitude, distance and velocity and changing time of start of the retro-burn.

a second thrust aiming to enter the potential field of Dimorphos. For a single target asteroid, a mission can be similarly designed with normal Keplerian orbital dynamics.

3. Results

Thus the self-transferring MASCOT-derivative can be successfully deployed from a safe distance to low gravity small bodies. The mission timeline for the Didymos binary system as given in Table 2 showcases the operation sequence for such deployments. The key parameters affecting the mission's success for a constant altitude deployment are the time at which the thruster is fired and the velocity error margin. If the thruster is fired too early then it takes a long time to descend down. For even earlier thrusts the lander fails to get pulled down by the secondary asteroid as it doesn't have the right energy for entering the stable manifold from the Lagrange 2 point. For varying heights of deployment, the key parameters that constrained the analysis were the time at which the thruster is fired and the thrust force which is used. The higher the thrust force, the higher are the uncertainties of the dynamics of the system. The attitude and position margins are less significant factors but need to remain in the acceptable ranges.

For the given mission a market research showed that several current state-of-the-art commercial-off-the-shelf (COTS) integrated GNC units and cubesat based cold gas micro-thrusters are available. The small size of these products make them integrable with the MASCOT architecture without any drastic changes to its structure. Furthermore, instruments on-board the novel MASCOT-derivative landers can also be used to complement the GOSSAMER instruments for a wholesome observation of the target body as well as for navigation during the cruise phase. An example can be the wide-angle MASCAM for assisting the optical navigation or a antenna to help in the bi-static radar measurements.

The GOSSAMER mission allows for a payload of up to 50 kg hence 3 of the 5 asteroids can be visited by the 17 kg MASCOT-derivatives. The multiple NEA rendezvous sequences found by Peloni et al. [i][j] were constrained to targets fulfilling NHATS criteria and having at least one PHA per sequence. Because of the natural size-frequency distribution of asteroids, many of the targets are small asteroids Ø <200 m of which most are fast rotators that would not allow a MASCOT lander to settle permanently even if it is delivered well below escape velocity of order cm/s. Thus, system-level trades can be made between having landers for up to 5 targets but some NEAs not 'accepting' them, having fewer but individually heavier landers that de-risk the proximity operations of the sailcraft, or/and slightly enlarging the sail area to achieve the same performance with 5 slightly heavier landers also capable of close looks involving non-permanent landings at very small NEAs. The only factors dependable on the solar sailing orbiter would be the attitude and velocity at which the landers are deployed.

Table 2 Mission Timeline for the proposed self-transferring MASCOT-derivative to Dimorphos in the Didymos binary asteroid system

Time	Mission Phase	Parameter Scope
0 min	Separation	The MASCOT-derivative (17 kg) is separated with a velocity of 100 cm/s at 229.5^0 attitude.
38 - 40 min	Begin of retro-burn	As it approaches with a velocity of 96 cm/s, a deceleration burn of 0.2N is fired at an altitude of 65 – 200 m altitude from the surface.
42-44 min	End of retro-burn	In about 82-90 s a velocity of 3cm/s at an altitude of 25-50 m is reached and the retro-burn ends.
52 – 120 min	Begin of landing phase	Lander is in free-fall for 10 min to over 2 h depending on how early was the retro-burn fired. Then it impacts the surface with a velocity of around 2.5 - 5.7 cm/s followed by a few hops before settling down on the asteroid.

4. Conclusion

The structural and technological robustness of MASCOT landers allows it to land ballistically on largely unknown bodies with a lower risk. Its unique hopping mechanism give it a freedom of locomotion on the surface of a micro-gravity body with lesser constraints from the topography than the wheeled or legged landers. Moreover, its low volume and low weight structure allow its accommodation on a unique solar sailing MNR mission such as the light-weight GOSSAMER solar sail. Its separate payload compartment can be easily customised based on the target bodies scientific missions. Thus in a period of 10 years as many as 5 different asteroids can be visited with both surveillance and sousveillance of these intriguing SSSBs.

The proposed GNC and propulsion enhanced MASCOT-derivatives reduces the mission risks further and allow the orbiter to observe the unique and unknown asteroids from a safe distance. The preliminary PCR3BP trajectory design and mission analysis show the success of such a lander to be at 97.4%. There is a wide scope for more interesting science missions that deploy the nano-landers for scouting for a science mission or before an asteroid mining campaign or for observing during an impact for a planetary defence exercise on a binary system.

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