NUMERICAL SIMULATIONS OF SURFACE PACKAGE LANDING ON A LOW-GRAVITY GRANULAR SURFACE: APPLICATION TO THE LANDING OF MASCOT ONBOARD HAYABUSA2.

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Introduction: The asteroid sample return mission, Hayabusa2 JAXA) was launched on December 3rd, 2014. It will reach the C-type near-Earth asteroid (162173) Ryugu in 2018 and bring back samples from its surface to Earth in 2020.

Hayabusa2 will release the European (DLR/CNES) lander MASCOT (Mobile Asteroid SCOuT) on the asteroid surface to perform in-situ measurements [1]. Ryugu's surface is expected to be composed of a granular layer (regolith), whose physical properties are currently unknown. MASCOT's behavior at landing, in particular its possible bounces, the traces left at the impact site, and the distance it may travel, will provide essential information about the nature of the regolith.

To predict and support the landing site selection, as well as to be able to interpret the outcomes of the landing, we ran a first campaign of about 450 numerical simulations of MASCOT landing and interacting with Ryugu's surface [2], accounting for its low gravity. Both MASCOT's and the soil's parameter spaces are investigated over a reasonable range to estimate their influences on MASCOT's trajectory.

Method: The simulations are performed with the parallel N-body gravity tree code *pkdgrav*, in which was implemented the soft-sphere discrete element method (SSDEM) to model the contact dynamics between the particles constituting the regolith bed [3].

We define the regolith by the grain sizes and various friction parameters (e.g., static and rolling frictions). Two kinds of regolith are considered, differing by the friction parameters of the grains, which are either moderate or gravel-like based on their angle of repose, allowing us to compare the impact outcomes as a function of regolith frictional properties. In this first study, the cohesion between grains is ignored.

We considered two types of grain size distribution, namely a gaussian distribution and a power-law distribution, both restricted to a relatively narrow size range. As power-law distributions require higher computation time, most of the simulation results obtained so far use a gaussian distribution, with a 1-cm mean radius and a 33% standard deviation.

We place the regolith bed in a cylinder whose width is about five times the lander's largest dimension to minimize undesired boundary effect. We also considered three different cylinder heights (regolith depth): 15 cm, 30 cm and 40 cm.

MASCOT was modeled as a 10-kg cuboid of six joined "reactive" walls – meaning they react to forces from the particles – plus a small prominence, also made of reactive walls, representing the sensor of the hyperspectral microscopic imager (MicrOmega). In most of the simulations, we assumed a constant structural coefficient of restitution of 0.6, as determined by the MASCOT team. However, we also ran simulations with different coefficients of restitution to investigate their effects.

Results: We first found that the stochastic aspects of the simulations are non-negligible. Consequently, we paid particular attention to the global trends and not to every behavior in its individuality.

To study MASCOT's behavior, we computed several characteristics of the impact, such as the collision duration and the MASCOT linear coefficient of restitution resulting from the impact (outgoing to ingoing speed ratio of MASCOT's center of gravity).

Here we present results in terms of distances between MASCOT bounces, time of travel and impact speed at second bounce/landing, as a function of regolith properties (friction parameters, depth, grain sizes) and first impact conditions (impact angle, MASCOT orientation and spin).

Evolution of MASCOT after the first bounce. For the full set of simulations, we computed the trajectory perfomed by MASCOT after the first impact, as well as the duration between two surface contacts. Figure 1 shows an example of distance traveled by MASCOT for the two considered regolith types, the five first impact angles and different coefficients of restitution of MASCOT itself. On figure 1, the regolith depth is 30 cm and MASCOT's first impact occurs on the flat face where MicrOmega is present, with no spin, at an impact speed of 19 cm/s and in a uniform gravity of 2.5×10^{-4} m/s^2.

We find that the higher the first impact angle from the vertical, the larger the distance MASCOT travels. The distance is also larger when the surface is made of gravel-like regolith. This is consistent with the larger linear coefficient of restitution of MASCOT after impact on the gravel-like surface, and therefore a larger outgoing speed. For all considered cases, the maximum distance traveled by the lander is of the order of 25 meters, which corresponds to the case of a gravel-like regolith with depth of 15 cm. In fact, a lower regolith depth results in non-negligible boundary effects at the bottom of the cylinder, which cause wave reflection, promoting outgoing motion of the lander.

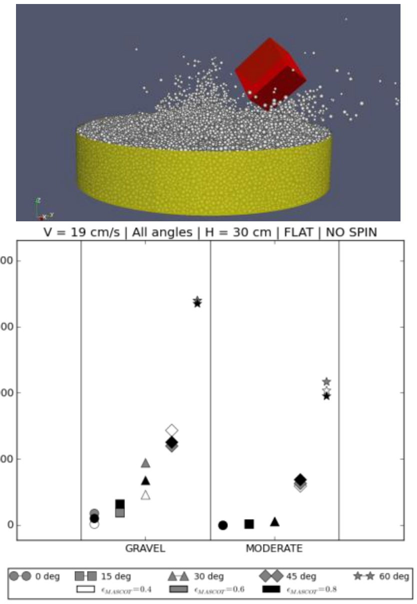

Figure 1. Top: Snapshot of a simulation of MASCOT interacting with the regolith. Bottom: Distance between the two first bounces of MASCOT as a function of regolith frictional properties, first impact angle, and MASCOT's structural coefficient of restitution. See text for details.

Figure 2 shows the time between the first two bounces for the same example. We find that the higher the impact angle from the vertical, the larger the time between two bounces. In the moderate friction case, for impact angles between 0 and 30 degrees, the lander actually remains on the surface (linear coefficient of restitution after impact is zero). The maximum travel time between two bounces is found to be of the order of 700 s, which corresponds again to the case of a gravel-like regolith with depth of 15 cm. Note that for all other cases, the maximum time is more typically about 250–300 s.

Impact speed and angle at second impact. In order to assess whether the second impact may lead to a second bounce, we computed the impact speed and angle at second impact. We generally find that the speed at second impact increases with the angle of the first impact. In other words, grazing first impacts of MASCOT result in higher speed and higher angle with respect to vertical at second impact than more vertical first impacts. For all considered cases, the maximum speed at second impact remains below 10 cm/s, i.e., half the first impact speed.

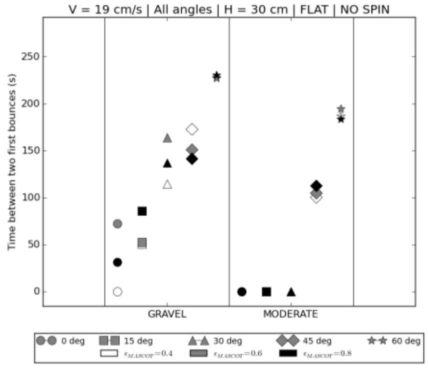

Figure 2. Time between the two first bounces of MASCOT as a function of regolith frictional properties, first impact angle, and MASCOT's initial coefficient of restitution. See text for details.

Conclusions: We performed a first set of simulations that already allowed us to observe some trends in the behavior of the MASCOT lander at first impact in the low-gravity environment of Ryugu. So far, we have considered two kinds of regolith frictional properties, without cohesion and with a gaussian grain size distribution. In addition to the analysis described here, we also plan to analyze deeper the traces left by the lander on the surface (e.g., crater's size and depth, distribution of ejecta, etc.). Future work will also consider cohesion between grains, power-law size distributions, the possible presence of a big boulder in the regolith bed, etc. The goal is to build a database of MASCOT landing characteristics that can help in the choice of the landing site, to constrain MASCOT's location on Ryugu, and to infer unmeasured regolith properties by comparing simulation outcomes (e.g., MASCOT's traces) with actual observations. We also plan to apply our numerical modeling and the analysis tools to other landing concepts onboard asteroid space missions.

References: [1] Ho, T.M. et al. (2016) *Space Science Reviews, MASCOT—The Mobile Asteroid Surface Scout Onboard the Hayabusa2 Mission*. [2] Maurel, C. et al. (2017) *Adv. In Space Res.*, in prep. [3] Schwartz, S. R. et al. (2012) *Granular Matter, 14:363-380*.

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