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Towards Drop Your Thesis 2018: 4.7 Seconds of Microgravity Conditions to Enable Future CubeSat Landings on Asteroids

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Abstract

An increasing number of interplanetary missions are aiming at visiting asteroids and other small bodies, since these may provide clues to understand the formation and evolution of our Solar System. CubeSats allow a low-cost solution to land on these objects, as opposed to risking a much more expensive mothership. The weak gravitational field on these small bodies may also enable the possibility of simply dropping a CubeSat from afar (i.e. ballistic landing). However, ballistic landing of an unpowered spacecraft may be feasible solely within certain asteroid locations, and only if sufficient energy can be dissipated at touchdown. If such conditions are not met, the spacecraft will rebound off the surface. It is likely that the necessary energy dissipation may already occur naturally due to energy loss expected through the deformation of the regolith during touchdown. Indeed, previous low-velocity impact experiments in microgravity seem to indicate that this is exactly the case. However, data from past asteroid touchdowns, Hayabusa and Philae, indicate the contrary. This paper describes the development of an experiment which aims to bridge the aforementioned disagreement between mission data and microgravity experiment; to understand the behaviour of CubeSat landing on asteroids. The experiment will also test a novel damping system made by origami paper that should increase the dissipated energy at touchdown. The experiment will take place at the ZARM Drop Tower in Bremen in November 2018. With the constraint of 5 drops, the experiment will measure the coefficient of restitution during an available time window of 4.74 seconds of microgravity conditions. A 1U CubeSat mock-up will be used to represent a future asteroid lander. In order to mimic the landing of actual missions, the mock-up will have a mass of about 4 kg and it will be given a velocity of 15 cm/s with minimal rotation. This will be achieved by an automated spring-based release mechanism. An asteroid simulant, ESA03-A KM Bentonite Granules will be used to replicate an asteroid mechanical properties at the surface. This paper reviews the final design and the engineering challenges of the experiment.
Keywords: Coefficient of Restitution, CubeSat Landing, Asteroid, Microgravity, Drop Your Thesis, ZARM drop tower

Nomenclature

ε: Coefficient of restitution value
γ: Angle of internal friction
$\theta(t)$: Orientation of the CubeSat to the horizontal
θ_0: Impact angle of the CubeSat
θ_{Tx}: Touch down angle x-coordinate
θ_{Ty}: Touch down angle y-coordinate
ρ_{bl} : Simulant loose bulk density
ρ_{bc} : Simulant compacted bulk density
ρ_{pd} : Simulant particle density
C: Normal dimension of CubeSat (10cm)
G: Centre of mass of the CubeSat
g_0: Earth surface standard gravity

H: Height of the CubeSat
h: Height of damping system
h_{RM}: Height of complete Release Mechanism system
h_s: Thickness of simulant in the container
h_{sc}: Height of simulant container
r_{sc}: Radius of simulant container
$r_{(t)}$: CubeSat rotational velocity at time
$V_{(t)}$: CubeSat velocity at time
V_R: Release velocity (after final contact with spring)
V_i: CubeSat velocity before impact (touch down)
V_f: CubeSat velocity after impact
KE_1: Kinetic Energy of CubeSat before impact
KE_2: Kinetic Energy of CubeSat after impact

Acronyms/Abbreviations

Coefficient of Restitution (COR)
Electromagnet (EM)
European Space Agency (ESA)
European Space Agency Exploration Sample Analogue Collection (ESA^{2}C)
Finite Element Analysis (FEA)
High Efficiency Video Coding (HEVC)
Japan Aerospace Exploration Agency (JAXA)
Kinetic Energy (KE)
Linear Ball Bearing unit (LBB)
Polyurethane Foam (PUR Foam)
Release Mechanism (RM)
Region of Interest (ROI)
Zentrum für angewandte Raumfahrttechnologie und Mikrogravitation (ZARM)

1. Introduction

Asteroids are of great importance to understand the evolution of the solar system. These vestiges of the solar system formation are still not well known, however their study could provide information on many aspects of the solar system formation and evolution, including the origin of life. While observations of asteroids have been performed from spacecraft in close approach, landing still remains a risky operation, albeit the only ways to obtain ground truth data and local measurement.
Philae lander (ESA) and Hayabusa (JAXA) have shown that landing on a body with extremely weak gravitational field is still difficult risk and challenge. CubeSats, however are small and low-cost with miniaturized payloads. In order to de-risk landing operations, CubeSats are today considered as potential landing systems for asteroid missions [1].

The extremely weak gravitational environment found in small bodies enables purely ballistic descent trajectories, on which for example, a CubeSat can be deployed from afar and allowed to fall to the asteroid's surface. However, unless sufficient energy is dissipated at touchdown, the vehicle will either fail to remain in the intended landing site or, in extreme cases, bounce off the asteroid altogether. The Land3U experiment will attempt to quantify the energy dissipation during such a touchdown, and explain the apparent disagreement between the low energy dissipation measured during the touchdowns of Philae and Hayabusa [2,3], and the very high energy dissipation measured by previous low-velocity impact experiments in microgravity [4, 5, 6].

The experiment seeks to provide insights into the engineering challenges that must be addressed by future asteroid missions; in particular when attempting to land on the surface of such low-gravity bodies. The aim of this study is to understand the behaviour of CubeSat landing on asteroids with an additional objective of developing a damping system that could increase the dissipated energy. A 1U CubeSat mock-up will be used to represent a future asteroid lander. In order to mimic the landing condition of actual missions, the mock-up will be given a velocity of 10-20cm/s with minimal tilting. This will be achieved by an automated release mechanism that will meet these requirements. An analogue of asteroid regolith will be selected to simulate its mechanical properties.

Land3U experiment will also fill the gap of knowledge on the influence of projectile shape in low velocity and low gravity collision. As previous studies used spherical shape projectile [2, 3, 6], Land3U will use a rectangular shape which is believed a more likely representation of future asteroid lander.

This paper presents the preparation for the Land3U experiment: the first section is dedicated to the simple modelling of the CubeSat touch down; then the experiment set-up is detailed by analysing each one of its subsystems, which include CubeSat structure, asteroid regolith analogue, ZARM Drop Tower, the release mechanism, the sensors and, finally the damping system. Then conclusion and perspectives are exposed in the last section.

2. CubeSat touchdown

An analysis of the dynamic behaviour of the CubeSat will be performed to model the rebound and understand the influence of velocity, mass, and rotation on the coefficient of restitution (COR) value. This behaviour should help understand the factors taken into account in the final experiment and their implications on a real landing.

The inability to embark complex landing system on CubeSat limits the capacity of landing on an asteroid. However, the work of Celik and Sanchez shows that completely ballistic landing opportunities (i.e. without any active control) indeed exist [1]. Celik and Sanchez show that the ability to reduce the normal COR to a value of 0.6 allows landing for a CubeSat on binary asteroids, with a landing velocity between 10cm/s to 35cm/s. This interval can be reduced for landing on the asteroid's most accessible regions, with the lowest velocities at impact being in the range of 10cm/s to 20cm/s. This interval of velocity was thus chosen as the targeted velocity for the final experiment.

This range of velocities is considered as low-velocity impacts. This type of impacts has been the subject of several studies [4, 5, 6], however key points for CubeSat remain not tackled. Previous studies used a spherical impactor and thus did not have rotation effects on their results. The level of microgravity plays also an important role when modelling the landing, as gravity allows the establishment of rocking motions [7]. The

importance of these effects could not be appreciated in previous experiments due to the fact that spheres were used as impactors.

The definition of the coefficient of restitution is the first step to take to be able to analyse the dynamic behaviour during an impact. The coefficient is a tool used in impact studies to allow a simple modelling of the complex transfer of energy to get useful information on the impacted bodies. This coefficient is influenced by lots of parameters specific to the objects impacting the surface, as well as the characteristics of the surface itself. The coefficient of restitution is hardly obtained by other mean than experimentation. However, to base our approach of this coefficient of restitution, we refer to Asteriou and Tsiambaos [7] and Mascot documents on the landing simulations [9, 10] to determine the definition of our coefficient of restitution to be studied.

Due to constraints in the volume available in the vacuum chamber used in the experiment, the team chose to study a 1U structure equipped with the usual mass of a 3U (4kg). It allows mimicking the kinetic energy of a 3U at impact. With a perfect vertical landing, the interaction of this 1U with 4kg should be the same as that of a 3U. However, the verticality might not be perfect and thus, Land3U team is working on models to understand the difference created. Indeed, the impossibility of obtaining the same inertia matrix and centre of mass of a 3U in 1U volume creates changes of behaviour when rotation is involved, as the lever arm is more important. The complexity of modelling the interaction of a rigid structure and a granular ground makes the creation of a simple and realistic dynamic model impossible.

However, the consideration of rigid and impenetrable objects, bouncing on an infinitely stiff surface, allows to understand the importance of the induced angular momentum. Clearly, impact angle must be reduced to minimum possible to ensure relevance of the results for a 3U landing system. This is achieved in the Land3U experiment with a guiding rail as described in Section 3.4. According to the aforementioned rigid model, the values obtained during the experiment should offer a good approximation of the coefficient of restitution of a real 3U landing system. Improvement of the model using finite element modelling and granular modelling of the simulant will be used to improve the results and understand better potential differences.

3. Experimental set-up

The experiment will take place in the ZARM Drop Tower, in Bremen, Germany. To perform this experiment, a capsule will be drop from a 146 m tall tower. The tower itself is under vacuum environment. However, the interior of the capsule given by the facility is not under vacuum condition. Since we are aiming to mimic the actual event on asteroids, an additional

vacuum chamber, which was provided by JAXA, will be set up inside the capsule. Our experiment will be placed within this JAXA vacuum chamber.

Figure 1 shows the experiment platform inside JAXA's vacuum chamber. The blue spring represents the release mechanism, the orange part shows a 1U CubeSat mock-up and the simulant is presented in brown. There are two cameras to observe the impact near to the surface of the simulant.
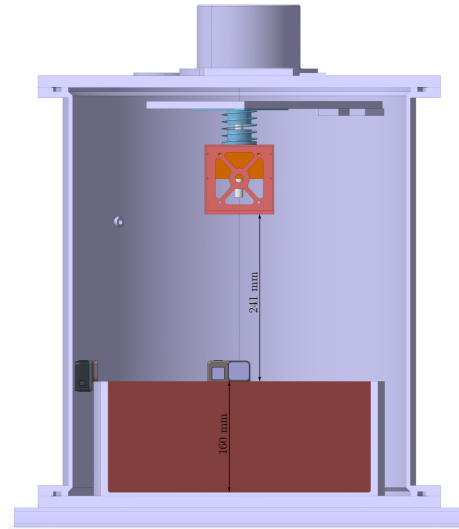

Figure 1 Cross section of experiment set up inside JAXA vacuum chamber

3.1. ZARM Drop Tower

Microgravity experiments on the Earth are usually performed using parabolic flights, sub-orbital rocket flights or drop towers. The ZARM Drop Tower in Bremen is the main facility of ZARM (Center of Applied Space Technology and Microgravity). It offers opportunities for short-term experiments (either 4.74 s for the drop mode and 9.3 s for the catapult one) under microgravity conditions. With a height of 146 m, the Bremen Drop Tower is the only laboratory of its kind in Europe. The ZARM Drop tower is ideally suited to simulate this microgravity environment, encountered by small asteroids. The level of microgravity provided could reach down to 10^{-6} g_0. Land3U experiments will requires around 4 seconds of microgravity conditions; 2 seconds are required from the release of the CubeSat to the impact, and another 2 seconds are used to observe the phenomena after the impact. Therefore, 4.74 s drop mode is suitable for this project considering 0.5 s not usable due the 10^{-6} g_0 level of microgravity settlement.

The experiment is to be set inside a capsule developed in ZARM for microgravity experiments. It is equipped with power source, sensors and connexions for external control. It will fall in the tower allowing the experiment set-up fixed inside to experience microgravity during 4.74 s. The interior of the capsule is

not in vacuum conditions, therefore a vacuum chamber, lend by JAXA, will be added in order to mimic both vacuum and microgravity conditions present on an asteroid. The Land3U experiment will be set up inside this chamber. Figure 1 shows the experiment platform inside JAXA's vacuum chamber.

Before the drop, the capsule will be held at the top of the tower. At the beginning of the drop, the capsule will start falling and will take 0.5 s before experiencing microgravity at the desired level. The moment it enters stable microgravity condition, a spring-based release mechanism will release the CubeSat with a velocity of 150 mm/s. The CubeSat will fall a distance of 24 cm, in order to have around 20 cm freefall between the release and the asteroid simulants. This distance allows the CubeSat to reach the ground with a limited influence of the release mechanism. After approximately 2 s, the CubeSat will hit the simulant and is expected to rebound and move upward during the next 2 s. The rebound of the CubeSat will be observed through cameras to determine the velocity of the CubeSat after rebound and pull the COR.

At the end of the drop, the capsule and experiment will suffer a deceleration force between 25g and 50g due to the ZARM decelerating the capsule at the tower ground (absorbed impact). These deceleration is done by crashing the capsule into cushions.

3.2. CubeSat external structure

Since the experiment's results must inform future missions to asteroids, the landing element of the experiment needs to replicate a potential future lander. A cubic form was then preferred to a spherical one and, amongst the small satellite bus range, the CubeSat standard was chosen for its current interest in asteroid related missions.

The first aim was to use a 3U CubeSat, as it is the expected minimum CubeSat size that will land on asteroids. However, due to the vertical space available in the vacuum chamber, a 1U CubeSat (see Figure 2) was selected and will be given additional mass to represent the same actual 3U CubeSat lander have, which is approximately 4 kg. The importance of mass is explained in previous Earth COR determination experiments [8] and thus a 4kg load was maintained in the Land3U experiment. The main particularity of this CubeSat is the presence in the top and bottom face of a hole in the middle to put the rod necessary for the release mechanism as a guiding system.
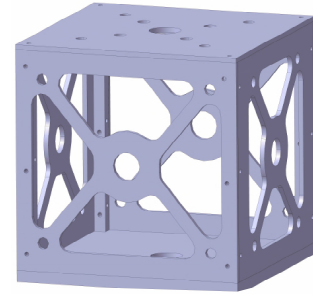

Figure 2 CubeSat 1U mock up

3.3. Asteroid regolith analogue

The aim of this work is to observe the behaviour of a CubeSat landing on the surface of an asteroid. There are four main objectives for the asteroid regolith analogue in order to yield an accurate and relevant result; firstly, selects/creates a regolith simulant that mimics well the expected asteroid surface condition; secondly, ensuring the rebound is merely effected by the simulant not by the container; thirdly to minimise tilting, to have flat and smooth regolith surface; and finally to ensure a similar characteristic of simulant between drop.

In this work, material selection is weighted on its similarity of mechanical and physical properties. European Space Agency Exploration Sample Analogue Collection (ESA^{2}C) stores their selection of material analogues in Natural History Museum (NHM), London. The materials available at ESA^{2}C range from Martian, Lunar, Phobos, Deimos, and C-type asteroid regolith. Based on available options, trade studies were performed to select the most representative of asteroid surface material. As a result ESA03-A KM Bentonite Granules is selected for this experiment. ESA^{2}C mentions that the simulant will represent the properties expected at the surface of Phobos, Deimos and C-type asteroids surface, although it does not have similar bulk densities to those reported for asteroids (e.g. C-type ranges between 1.6 – 2.3 g/cm^3), nevertheless other physical characteristic are similar [10]. Based on the data sheet given by ESA^{2}C, the grain morphology are rounded to very rounded, smooth, ranges from low to high sphericity. The bulk density ranges between 1.13 g/cm^3 (loose, ρ_{bl}) to 1.25 g/cm^3 (compacted, ρ_{bc}); the porosity ranges between 56.2% (loose) – 51.4% (compacted). The cohesion is 10.4 kPa with angle of internal friction, γ of 27.9°. The particle density, ρ_{pd} is 2.44 g/cm^3. At Cranfield University, 25 g of sample were tested.

Table 1 to define in more details the particle size distribution of the simulant. Based on the data sheet given, the mass is 50% at grain size of below and above 2.44 mm.

Another aspect that might affect the measurement is the surrounding wall, lateral-normal confinement; the experiment desires to measure COR that is affected merely by the simulant not by the container; which lead to have a minimum simulant thickness and width requirements. Murdoch studied low-velocity impacts into granular material under reduced gravity condition. A 2kg, 10 cm diameter aluminium sphere was used as the impactor into quartz sand in low effective gravities ($\sim$0.2 – 0.1 m/s^2); the materials give bulk density of 1.79 g/cm^3 with individual density of 2.65 g/cm^3; the grain size ranges between 1-2.5 mm and half the sample mass below and above 1.83 mm [5]. Obviously, there are dissimilarities between Murdoch and land3U experiment, however data from Murdoch provides indication on how the collision would behave and the penetration. Murdoch provides insights on the collision duration at impact velocity between 0-35cm/s. At Land3U experiment, the impact velocity ranges between 10-20cm/s window and based on Murdoch's work, the collision duration ranges between 0.12-0.22 s and penetrates between 0.5-1.5 cm. Calculation was made with assumption of COR between 0.5-0.8 and collision duration ranges stated previously. Thus, a 4 kg mass with impact velocity of 10-20 cm/s would generate impact force of 2.7-12 N.

Land3U predicted the vertical influence below the surface of this impact at the regolith by using *Boussinesq* method [11]. This would understand the depth required to ensure the rebound is only influenced by the soil not the container wall. The method could determine the vertical stress increases in a soil mass. Using *Boussinesq* method-influence of depth in shallow foundation, and assuming Poisson ratio of 0.5. The maximum stress vertically and horizontally ranges between 0.0076 – 0.00048 N/mm^2 and 0.0038 – 0.00024 N/mm^2 from zone 10 – 100 mm depth and radius. The stresses beyond that level should be very low. Based on how the experiment will perform, 160 mm is the maximum allowed thickness for the simulant and 200 mm radius is the maximum size for the container. At this radius and depth, there are still stresses influencing and to have a container without those influencing stresses in this experimental platform in not achievable. However the stresses acting in it are extremely small. This scenario is expected to be sufficient and will influence the behaviour of the impact at minimum level.

To have accurate COR measurement, tilting after the impact should be minimised. Hence, the regolith container must present a smooth and flat surface at each single drop. Therefore, the simulant thickness has to be identical, so that presents a flat surface parallel to the base of container and vacuum chamber. A total of 22 kg of ESA03-A KM Bentonite Granules will be placed inside the container.

Table 1. Particle size distribution and sample mass from ESA03-A KM Bentonite Granules.

Grain size	Particle size distribution (%)	Sample mass (g)
< 53 µm	0.39	0.10
53 µm - 63 µm	0.21	0.05
63 µm - 125 µm	0.48	0.12
125 µm - 150 µm	0.24	0.06
150 µm - 250 µm	0.19	0.05
250 µm - 500 µm	0.12	0.03
500 µm - 1.00 mm	1.97	0.49
1.00 mm - 2.00 mm	36.69	9.16
2.00 mm - 2.36 mm	16.96	4.23
2.36 mm - 3.35 mm	26.27	6.56
3.35 mm - 4.75 mm	16.47	4.11
>4.75 mm	0.00	0.00
	total sample mass	24.97

3.4. Release Mechanism

The aims of the RM are to perform its requirements with a high reliability, to interlink and compliment interfacing subsystems, and to consider Land3U's budget and time constraints.

The requirements of the RM are to provide the CubeSat with a touchdown velocity in the range of 10-20 cm/s, to guide the CubeSat to within ± 2 degrees of tilting upon touchdown, and to ensure touchdown velocity per drop are all within± 1 cm/s. The CubeSat release time will be directly 500 ms after the initial capsule drop, in order to damp out capsule initial-release vibrations.

From a general perspective, the RM system consists of: a Lite Pressure^{TM} Compression Spring, an EM with a threaded centre hole, a precision rod which screws into the EM's centre hole, a CubeSat-magnet interface, and a LBB which is held in place by a shaft within the CubeSat. The configuration of the RM is represented by Figure 3 Release Mechanism – CubeSat layout. While each individual item listed above provides a unique function, they all try to best converge towards the requirements selected by the global perspective of the Land3U team.
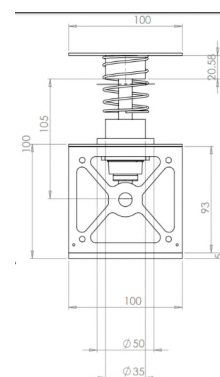

Figure 3 Release Mechanism – CubeSat layout

In order to test each individual component, a prototype release mechanism was designed per item under test. Since the touchdown velocity and consistency of velocity interlinked two of the main requirements, the spring tests were rigorously performed and analysed.

The first test utilised the Instron machine at Cranfield University to sample potential springs, and checked the reliability and durability of the spring's properties. The key factors were spring compression percentage and spring constant.
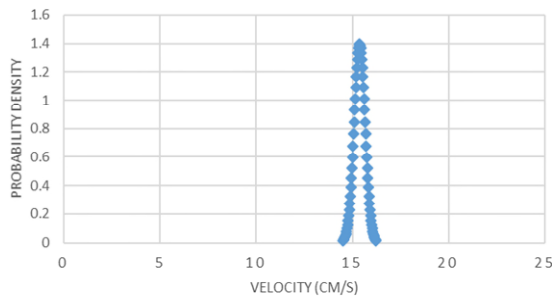
Figure 4 Achievable velocity and consistency for 100 spring ejections

The second test entailed a pendulum design with Arduino light gates. A CubeSat mock-up was pushed at discrete spring compression intervals by means of adjusting a threaded screw; this gave an understanding of consistency of velocity and touchdown velocity. The test gave the mean and standard deviation of 100 ejections for multiple springs. This concluded for the optimal spring; the average ejection velocity $\mu = 15.4$ cm/s at $\sigma = 0.286$ cm/s could be achieved, ensuring both requirements would very likely be met if the test and prototype had no significant errors. The correct compression had certain ambiguity however, in the sense that there were external forces of resistance mentioned in the next paragraph, which would predict a smaller velocity than would actually be achieved in a lower friction vacuum chamber environment.
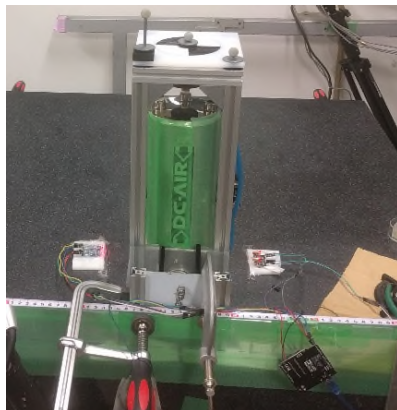

Figure 5 Air-Bearing table test, set-up at Tohoku University, Japan

A third air-bearing table test was performed using the lab facilities at Tohoku University, to provide a more precise spring compression length, and to confirm the accuracy of the previous results from a new test/set-up's perspective. The test involved an air bearing table, a precision camera tracking system, and Arduino laser gates. These improvements eliminated friction from the pendulum string, eliminated the transfer of KE to GPE along the pendulum arc, observed a 4 kg mass instead of a 1 kg mass (less derivation required), observed the change in average velocity per 4 mm of compression, and proved a higher accuracy of velocity tracking.
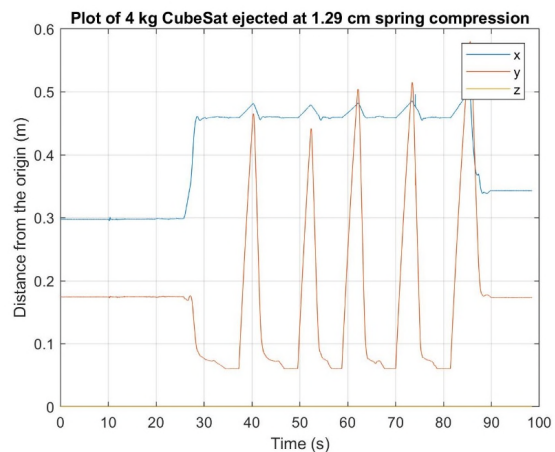

Figure 6 Five CubeSat ejections in targeted y-direction

The RM required consideration of the CubeSat tilting, and will control the tilting up until the point it leaves the precision rod. Within this period of time, it will be guided by SKF's next generation D-series LBB, with an integrated double lip seal (2LS). The 2LS eliminates the need for maintenance in an ambient Earth environment, and was perhaps one of the best options to prevent outgassing of the lubricant contained around the balls in the near vacuum (100 Pa) test environment. The prevention of outgassing will enable the friction from the ball bearing to remain consistent, and therefore the consistency of velocity per drop. The shaft and LBB contained within the CubeSat are symmetric about the top plate's x-y axis on the CubeSat, to best accommodate the items within the CubeSat; and increase the moment of inertia about the top plate's x-y axis, providing a more resistant rotational inertia.

Two CubeSat-magnet interfaces have been designed to accommodate the required spring compression, enable a flat plate push, and to remain 'magnetically soft' with a narrow hysteresis loop. A silicon-iron alloy is currently predicted to optimally meet these requirements, and is the likely option to proceed into the final design. A residual magnetism test will observe whether preventative measures must be taken to avoid

CubeSat-magnet interface and electromagnet sticking, and whether it will absorb KE imparted by the spring. The delayed release time will be tested at Cranfield with an Arduino system, as well as the reliability of release for the two CubeSat-magnet interfaces designed. This will be performed as part of a pre-Bremen global integration test, however timed release for the final experiment will be controlled by ZARM's Capsule Control System (CCS).

3.5. Cameras and estimation of COR

The Land3U experiment performs measurement of velocities just before the impact and just after the rebound if it happens.

For a long time, space exploration relied on space observation where the spacecraft would at most orbit around the object of interest to perform data collection through embarked sensors. However, landing on the surface allows more data to be collected but adds the issue of the landing accuracy and the continuous control of the spacecraft while it is approaching the landing site. One of the most promising field for automation of landing comes from the near real-time image processing using cameras embarked on the spacecraft. This method is known as optical navigation and has already some application in the space industry however it is most developed in the robotic field for Earth system where nowadays the ascent of artificial intelligences methods allow a sky-rocketing of this ability. The Land3U team considered the use of such technology as the best approach to obtain the information required for the simulation of a CubeSat landing on asteroid in a drop tower.

Optical navigation allows the spacecraft to know its position compared to observed objects or reference points. The development of landing applications using this method of navigation is implemented through the detection of features on the observed celestial body. This technique has been especially developed for celestial bodies without atmosphere so their surface can be observed which remains constant for the period of observation. Atmosphere would make important changes to the observed surface and would make it hard to create reference points. The work of Meng [12] describes such method application for lunar probing missions. The advantage of the features detection is that it can use one celestial body surface for several reference using markers such as meteoroid impact or shadowed region due to topography. This method appears the best approach for exploration of small space bodies as their form are usually more complex than a simple ovoid but have several features than can be identified by algorithm to associate landmarks.

Optical navigation has greatly risen from the development of autonomous system such as robots but even more recently with drones' development. Several papers are flourishing on the development of autonomous guiding system for drones such as McGuire's [13]. The axis of development of this robotic navigation is also segmented with different methods and algorithm. A method used for this optical navigation is the detection of edges to define the contour of the tracked object. Knowing its real structure, the tracked contour can be fitted to a real projection of the object. When several cameras are available, a 3D reconstruction can be directly performed. The edge detection is a powerful method that allows the detection of the contour of objects of interest, which can then be identified [14]. It is usually complemented by a matching method where the geometry of the object is described (CAD drawings) and which the algorithm uses to identify the object among other edges [15, 16].

Land3U team developed two image processing method for velocity measurement using respectively the features detection method [16] and the edge detection method [17], see Figure 7. The video will be obtained by GoPro Hero6 black cameras, which were selected due to their capacity to record in HD with a 240fps that will allow a better capacity for the processing to detect the features on the recorded video. The high frames per second increase the accuracy of the estimation using a least square estimation of the velocity from the velocity measurements, see Figure 8.
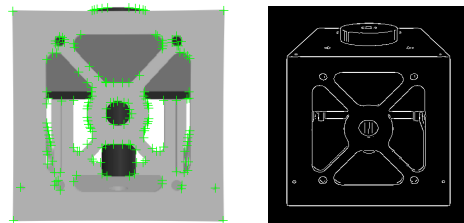

Figure 7 Harris features [18] (left) and Edge Detection: Canny edge detection [17] (Right) applied on the CAD modelled CubeSat
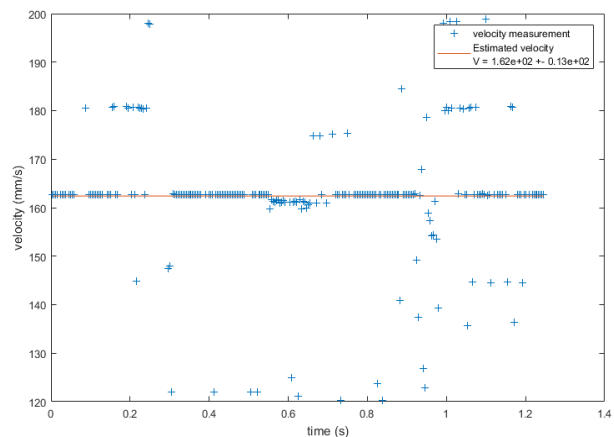

Figure 8. MATLAB plot of velocity estimation on a computer rendered video using edge method

3.6. Damping system

The aim of the damping system is to absorb the energy of the landing of the CubeSat, by reducing the post-impact velocity as much as possible. This will be achieved by using a passive damping system, since an active one would be unlikely to be able to deploy during the time spent in microgravity in this experiment.

This subsystem will change the value of the COR measurement, with the expectation that it will demonstrate a much lower COR than that achieved without the system in similar landing conditions.

In order to evaluate the different concepts, initial testing was carried out. This involved swinging a pendulum, with a mass of 4 kg, along with an aluminium plate and the concept damping system against a wall. The aluminium plate represented the base of the CubeSat. The angle from which the pendulum was released was calculated based on the velocity range and the length of the pendulum. The rebound angle was measured, and from this the energy absorption of the concept was determined. This test is represented in in Figure 9.

Figure 9 Experimental set up, showing 4 kg mass, aluminium plate and protractor.

Origami paper cubes gave best result, with greatest energy absorption by showing lower COR, as summarised in Table 2.

For the uncertainty, a t-distribution was assumed with a 95% confidence interval.

The chosen method is thus the four origami cubes attached to the base of the CubeSat. This was selected for the damping system since it absorbed the largest quantity of energy in testing. It is also very lightweight, around 610 grams including the mass of the adhesive used to attach the system to the base of the CubeSat. Figure 10 shows the attached origami cubes at the base of the CubeSat

Table 2 Mean COR over velocity range or 0.1-0.2 m/s for two different materials

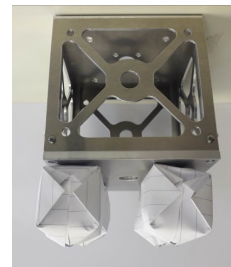| Material	Velocity (m/s)	Mean COR
No system	0.1	0.33 ±0.00
No system	0.2	0.39 ±0.00
Four origami cubes	0.10	0.41 ±0.16
	0.20	0.33 ±0.00
Memory foam (10 mm)	0.10	0.44 ±0.16
	0.20	0.46 ±0.04

Figure 10 Origami cubes attached at the base of a CubeSat plate

4. Conclusions and perspectives

This paper describes the development of subsystem design towards Land3U experiment.

We have designed a 1U CubeSat mock-up. Due to the platform of the experiment, to have a 3U CubeSat is not achievable. However the first analysis and the measures adopted to limit the tilting should provide results comparable to a COR obtained for a 3U.

Material selection to replicate the ground condition of C-type asteroids was also selected. A total of 22 kg ESA03A-KM Bentonite from ESA2C will be used in this experiment. Due to limited space and volume inside the vacuum chamber, a current width and thickness of the regolith will still have the influence from the wall. However, this is extremely low and expected to influence the impact behaviour in a very minimum level.

The performance of the release mechanism during the experiment will show the capacity of a spring electromagnet coupling to provide low velocity to a CubeSat. The consistency of this subsystem is a key factor for the success of the experiment.

The use of origami structure as a damping system might open a new field of application of this topic, which offers new solutions that previous technology could not achieve.

While some integration and electronics will be performed before the Drop Your Thesis campaign, the team will also improve the scientific output of this experience in the result analysis. A modelling of the CubeSat behaviour will include finite elements and granular modelling to fit the results of the experiment. The use of video recording as the measurements will allow improving tracking methods and analysing the attitude evolution of the CubeSat for determining the influence of rotation on the COR. Other outputs might also be possible such as particles dispersion from the video analysis.

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