FROM THE ROSETTA LANDER PHILAE TO AN ASTEROID HOPPER: LANDER CONCEPTS FOR SMALL BODIES MISSIONS

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ABSTRACT

The investigation of small bodies, comets and asteroids, can contribute substantially to our understanding of the formation and history of the Solar System. In situ observations by Landers play an important role in this field.
The Rosetta Lander – Philae – is currently on its way to comet 67P/Churyumov-Gerasimenko. Philae is an example of a ~100 kg landing platform, including a complex and highly integrated payload, consisting of 10 scientific instruments.
Other lander designs, more lightweight and with much smaller payload are currently investigated in the frame of a number of missions to small bodies in the Solar System.
We will address a number of possible concepts, including mobile surface packages.

1. INTRODUCTION

This paper discusses Lander concepts for small atmosphere-less bodies in the solar system (asteroids and comets). ESA's cornerstone mission Rosetta will be the first to rendezvous with a comet (67P Churyumov-Gerasimenko) in 2014 and to deploy a lander (Philae) on the comet's nucleus (see chapter 3). Historically, there are only two missions which reached the surface of a small body: the NEAR spacecraft touched down on asteroid Eros [1] and Hayabusa attempted to take samples from the surface of Itokawa and is currently on a trajectory leading it back to Earth [2].

One aspect of the paper is a review of various lander concepts for small bodies missions, allowing a comparison of benefits and drawbacks when planning new missions with certain boundary conditions, like available mass, mission duration or cost.
Starting with the technical specifics of landing on low gravity bodies (chapter 2), an overview of the Rosetta Lander Philae is given (chapter 3). This emphasizes on technical aspects, which may be of relevance for other in-situ missions to small bodies in the solar system.
In-situ probes can deliver a much higher scientific return if mobility is possible to explore more than one site. Chapter 4 discusses mobility concepts for low-gravity environments including current developments (the MASCOT hopper).

Several small body missions with Landers are presently under investigation; emphasis has been made on the asteroid sample return mission Hayabusa-2, currently studied by JAXA [3], as a next step after Hayabusa-1. Also missions aiming for sample return can be significantly enhanced by the implementation of in-situ surface packages since those help to constrain the geological and physical context of the samples and provide a hold on the evolutionary history of the body by probing its interior. Mobility can even "scout" the most interesting sampling sites on the surface (see [4]).

2. LANDING ON LOW GRAVITY BODIES

Landing on comets or asteroids, which are generally bodies with very low gravity is, in principle, very different to the landing on a planet or large satellite. In a typical case, only very low impact velocities will occur at touch-down. However, re-bouncing becomes a significant issue and anchoring is required for most scenarios [5].
Another important aspect for all comet or asteroid landers is the great uncertainty regarding their surface and mass properties [6]. Surface strength and local topography are basically unknown until investigated from close distances.
The Rosetta Lander, Philae, is an example for a small body Lander that will be the first ever to land on a comet, when being delivered in 2014.
When designing Philae, engineering models for the comet surface properties covered a range for the compressive strength between 60 kPa and 2 MPa [7]. The surface roughness is completely unknown.
The results of space missions to various asteroids and comets indicate that these bodies show a very wide range of surface characteristics and are very different to each other.
Any design for a Lander to a small body has to cope with a very wide range of possible surface properties, gravitational parameters and overall shape (in particular, if this body has not been visited by spacecraft before).

3. PHILAE, THE ROSETTA LANDER

3.1 Scientific Background

Comets remained in the Oort cloud or the Kuiper belt, far away from the sun since the formation of the Solar System about 4.6 billion years ago and, in contrast to the planets which underwent evolutionary processes during their history, they are believed to have retained a record of the original composition of the proto-planetary disk in which they were formed [8].
Due to gravitational effects some of those bodies get injected into orbits that bring them closer to the Sun (and the Earth).
In the primeval dust clouds from which the sun, planets and comets originated, complex molecules such as amino acids or di-amino acids may have formed [9] . In comets those may have been preserved over billions of years. Thus, comets may have played a significant role for the origin of life since they transported organic matter to the early Earth [10].

The scientific objectives of the Lander comprise [11]:

- The determination of the composition of cometary surface matter: bulk elemental abundances, isotopes, minerals, ices, carbonaceous compounds, organics volatiles - in dependence on time and insolation.
- The investigation of the structure, physical, chemical and mineralogical properties of the cometary surface: topography, texture, roughness, mech-anical, electrical optical and thermal properties.
- The investigation of the local depth structure (stratigraphy), and the global internal structure.
- investigation of plasma environment

3.2 System Overview

Rosetta is a Cornerstone Mission of the previous Horizon 2000 ESA Programme. The mission was launched in 2004 and will reach its target, comet 67P/Churyumov-Gerasimenko in 2014 [12,13]. After an intense phase of remote investigation of the comet nucleus, about 7 months after arrival, at a heliocentric distance of about 3 astronomical units (AU) the Rosetta Lander, Philae, will perform the first ever landing on the surface of a comet.

The original concept for Rosetta included two small (45 kg) surface science packages, Champollion, to be provided by a JPL/NASA and CNES consortium 14,15] and RoLand, which became the basis for the later Rosetta Lander, Philae [16]. These concepts are still of interest, when designing new small bodies missions, providing opportunities to include surface packages in the ~50 kg range.

Lander Design
The Lander, which has an overall mass of about 98 kg (including 26,7 kg of science payload) is based on a carbon fibre / aluminium honeycomb structure, a power system including a solar generator, primary- and secondary batteries, a central data management system and an S-band communications system, using the Rosetta Orbiter as relay [11]. Table 1 shows the mass breakdown, fig. 1 a schematic view of the lander.

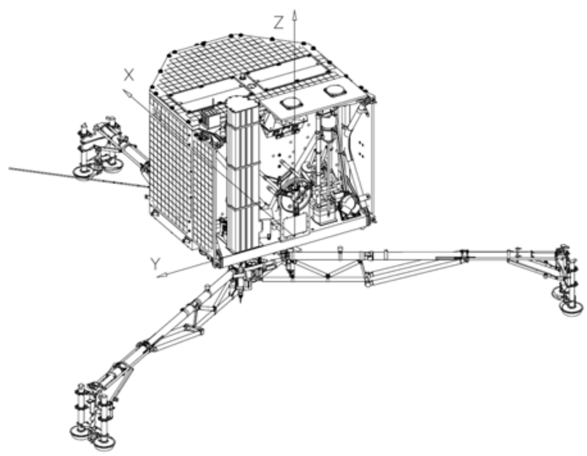

Figure 1: Rosetta Lander, Philae, in landed configuration

Table 1: Mass breakdown of Rosetta Lander, incl. subunits on Orbiter [11]

Unit	**Mass [kg]**
Structure	18,0
Thermal Control System (/MLI)	3,9 (/2,7)
Power System (/ Batteries / Solar Generator)	12,2 (/8,5/1,7)
Active Descent System	4,1
Flywheel	2,9
Landing Gear	10,0
Anchoring System	1,4
CDMS	2,9
TxRx	2,4
Common Electronics Box	9,8
MSS (on Lander), Harness, balancing mass	3,6
Payload	26,7
Sum [Lander]	**97,9**
ESS, TxRx (on Orbiter)	4,4
MSS, harness	8,7
Sum [incl. Orbiter units]	**111,0**

The thermal control system of the Lander is designed to keep the so called “warm compartment” (thermally insulated experiment platform underneath the hood) within an acceptable temperature range (-55°C to +70°C) on the comet nucleus with uncertain rotation, at distances between 3 and 2 AU from the Sun (goal is to reach even 1,3 AU). This is challenging as no radioactive heater units (RHU´s) were used.
The design, based on very good MLI insulation, electric heaters and thermal absorbers can be seen as a feasibility demonstrator for future missions with similar requirements [17].

During cruise the Lander is attached to the Orbiter (figure 2) with the MSS (Mechanical Support System) which also includes the push off device, consisting of three lead screws that will separate the Lander from the Orbiter with high accuracy and a pre-adjustable velocity between 0,05 and 0,50 m/s. In order to cope with the possible failure case that the Lander is stuck during push-off there is also an emergency release, ejecting Philae with a spring at a pre-defined velocity of about 0.17 m/s.

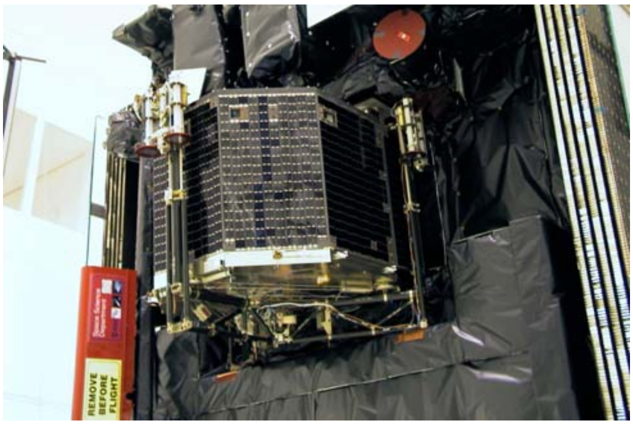

Figure 2: The Rosetta Lander Flight Model, mounted to the Orbiter

On the comet surface, Philae will rest on a landing gear forming a tripod. This tripod is connected to the structure by a mechanism that allows rotation of the complete Lander above its legs and some limited (~5°) adjustment to surface slope by a cardanic joint. It will dissipate most of the kinetic impact energy during landing by an internal damping mechanism. The Landing Gear needs to be optimized for the expected range of impact velocities. Thus, due to the change of target comet from 46P/Wirtanen (small, about 700m radius) to 67P/Churyumov-Gerasimenko (average radius: about 2 km; Lamy et al., 2007) additional stiffening had to be applied [18].

Separation, Descent, Landing and Anchoring

The exact descent and landing scenario for Philae is strongly depending on the actual properties of the nucleus of Churyumov-G., like shape, state of rotation and its gravity field. Also the gas production of the comet at 3 AU and the possible existence of jets need to be considered, since gas drag may alter the trajectory significantly.
Consequently, the detailed planning of the descent can only be performed after an intensive observation period from orbit, analyzing the remote sensing data, including high resolution images of envisaged landing sites and determination of the gravitational field by radio tracking of the Orbiter.

When sufficient information on the target has been collected and analyzed, a scenario will be worked out, based on a separation from the main spacecraft in orbit (it is desirable to perform this at low altitudes, i.e. 1 to 2 km), lander attitude stabilization with an internal flywheel, the optional use of a one axis cold gas system (propelling the lander “downwards”) and allowing sufficient time to perform system relevant tasks (e.g. unfolding of the landing gear) as well as the collection of science data.
A typical descent will take 30 min to 2 hours. Mission analysis shall provide a solution where the Lander z-axis as well as the impact velocity vector are both vertical to the comet surface at the landing site. However, local slopes up to 30° can be tolerated by the landing system (although the robustness of the landing depends on the impact velocity).
At touch-down, the cold gas system will provide downward-thrust and the anchoring harpoons will be fired. The harpoons, on a tether, shall provide good fixation to ground for a wide range of surface parameters for the rest of the mission [19].
Additional anchoring will be provided by ice-screws implemented in the feet of the Lander.

The whole complement of separation-descent-landing-anchoring equipment (SDLA) is a complex set of subsystems, which need to be operated with carefully planned timing and utilizing as much information on the target as available.
When considering future lander missions, a considerable spin-off from the Philae SDLA design can be utilized [5].

3.3 Operations with respect to mission phase

<u>Cruise</u>: Nominal Lander Operations include regular health checks of the system, subsystems and instruments during cruise, as well as the system preparations for separation (like adjustment of the eject mechanism or spin-up of the flywheel).
<u>Separation-descent-landing (SDL):</u> Some science operation is planned to be performed first during descent (e.g. descent imaging, magnetic field and plasma measurements).
For the comet phase after landing the Rosetta Lander radio link will be realised through the Orbiter as a relay

station. Lander data transmission will be scheduled according to the visibility of the Orbiter from the landing site and the available data link from Rosetta to Earth. In between, data will be stored temporarily onboard the Lander and/or the Orbiter. In case of direct radio-frequency transmission the round-trip communication time between the ground and the Lander will be up to 50 minutes. Therefore Lander on-board autonomy is used to ensure that Philae will be operational during the entire on-comet phase. The on-comet phase is divided into a First science sequence (FSS) and the long-term science phase (LTS).
FSS: During a first scientific sequence of about 120 hours, while the Lander will be powered to a large extent by its primary batteries, several instruments and subsystems can be operated simultaneously. Each experiment shall be operated at least once.
LTS: In the following long term operations phase the experiments will be performed mainly in sequence. The data evaluation will be carried out primarily offline, while the preplanning activities will be performed in parallel. Lander experiment operations are planned to last up to a few months on the comet surface.

3.4 Scalability of the Philae design

The Philae design can be scaled in mass and size to some extent; internal DLR studies [20] show that similar landers for asteroids can be designed in a mass range down to about 40 kg and probably well beyond 150 kg. For very small systems (<< 50 kg), other concepts will be more adequate.

4. MOBILITY CONCEPTS

Mobility of any surface element on a low gravity body requires different approaches than on planets or larger moons. Roving by wheeled vehicles is practically impossible, since the required force to the surface providing the necessary friction is not available [21].
Alternatively, surface elements could move with relatively low effort by means of propulsion systems (e.g., by cold gas thrusters) or using mechanically triggered jumping; the latter discussed in more detail hereafter. For landers without attitude control during descent, a self-rightening mechanism has to be foreseen for proper orientation on the surface after touchdown or after a mobility operation.

4.1 Historic Missions

The idea for hopping systems for extraterrestrial application goes back to Hermann Oberth in 1959 [22]. The idea was further elaborated e.g. by Seifert in 1967 [23].

The first space mission that actually included a hopper was Phobos 2, launched in 1988 [24]. The overall mass of this hopper, PROP-F, was in the order of 45 kg including the actual descent module as well as a so-called pacifier, designed to absorb part of the impact energy [25]. PROP-F would have been delivered from the main spacecraft at a distance of one to two kilometres to the surface of the Martian moon Phobos. Nominal impact at Phobos´ surface was planned to be around 5 m/s; descent time only a few minutes. After touch-down the pacifier was to be ejected and a self-orientation mechanism, based on whiskers would have up-rightened the hopper. After some measurements it could have jumped to another location. The overall operations time was limited to about 4 hours and a maximum of 10 jumps (driven by the capacity of the battery, 30 Ah). Fig. 3 shows an image of a model of the hopper, fig. 4 illustrates the concept of self-uprightening. For a more detailed description of PROP-F see [26].

Figure 3: The Phobos Hopper (courtesy: VNII Transmash)

Unfortunately, the communication with the Phobos spacecraft was lost before delivering the hopper to the satellite surface.

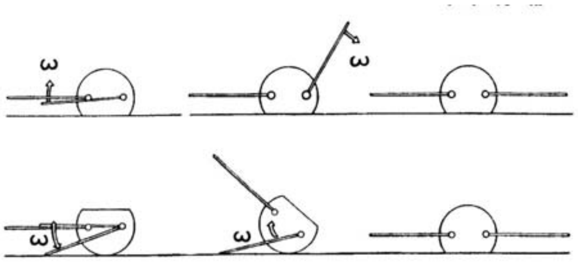

Figure 4: PROP-FP uprighting concept [26]

A much smaller device than the Phobos Hopper, intended to land on Itokawa, the target asteroid of the Japanese Hayabusa mission, was Minerva [27,28].
The mass of Minerva was only about 0,6 kg. It was equipped with two CCD cameras, sun sensors and thermometers as payload. The robot had a diameter of 120 mm and would have hopped by means of an internal torquer.
Unfortunately, in November 2005, Minerva missed the asteroid after being deployed by the mother spacecraft from an altitude of about 200 m [2].

4.2. Applications for future missions

In the light of a number of ongoing studies for missions to small bodies in the solar system also mobile surface science package are currently considered. As an example, MASCOT, a device with an overall mass of about 10 kg is proposed as payload for the Hayabusa 2 mission [4,29].
Fig. 5 shows a possible outline of MASCOT, Fig 6. a schematics of a jumping sequence.

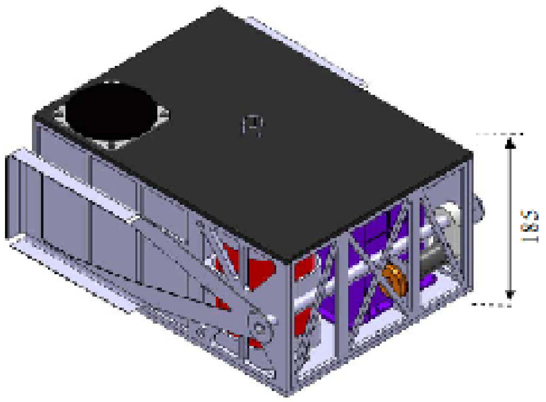

Figure 5: Design of MASCOT according to [30]

The whiskers (or “arms”) would serve for both, the hopping actuation as well as the up righting, in case of an upside-down landing. It has to be noticed, that all actuations have to be performed carefully and slowly on a low gravity body.

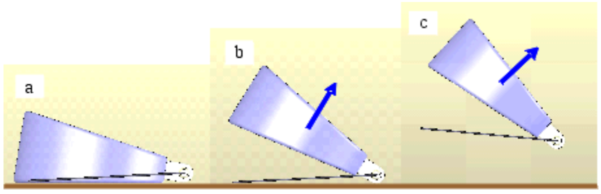

Figure 6: Hopping concept (courtesy: VNIITransmash)

A slightly different concept of mechanically triggered jumping includes accelerating masses inside the lander body. Depending on the parameters, turning or hopping can be achieved. These concepts are presently under intense investigation in the context of the MASCOT project at DLR.

5. CONCLUSIONS

Few spacecraft (NEAR and Hayabusa) have reached the surface of asteroids yet; a dedicated comet lander (Philae) is on its way to its target, an active comet. The scientific return of any rendezvous mission to small bodies is greatly enhanced by deploying a lander on the surface of that body, whether to complement the orbiter’s remote sensing observations as in the case of Rosetta or providing context, unperturbed properties and clues to bulk properties and evolutionary history in the case of upcoming sample return missions. We have discussed the technical design of Philae and its scalability as well as alternative concepts, in particular for smaller landers and landers with mobility. The latter can be a cost-efficient way to explore multiple sites of a small body.

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