A FAMILY CONCEPT FOR SMALL BODY LANDER STRUCTURES BASED ON MASCOT

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ABSTRACT

The DLR Mobile Asteroid Surface Scout (MASCOT) is an approx. 10 kg shoebox-sized lander platform developed for the Japanese HAYABUSA2 Asteroid Mission. MASCOT landed at 3. October 2018 on to the asteroid Ryugu (formerly 1999 JU_3) where it conducted in-situ experiments partially autonomously and for more than two asteroid days (17 hrs) at two different locations. After MASCOT, several direct follow-on studies were performed, for example MASCOT2 for the AIDA/AIM mission proposal, the ALDERAAN proposal and currently MASCOT3 for a potential Apophis lander in the frame of the RAMSES mission. The goal of this paper is to outline the structural development and peculiarities of various small body landing systems based on MASCOT. Apart from the lander itself, also different interface structures' designs are presented. In detail, the paper discusses the structural design variations and how the design was adjusted over time in order to respect the corresponding sets of given mission as well as system requirements. The paper concludes with the presentation of family concept for small body lander structures for landing systems of approx. 10-30 kg. Such a family concept is adaptable to a range of mission scenarios and can be mounted 'piggy-back' to various mother spacecrafts.

DLR'S SMALL BODY LANDERS

In-situ small body exploration by means of landers is a rather recent attempt in the history of space exploration. As stated in [1] the earliest attempts were FOBOS-1 and -2 in 1988 and the first successful landing performed in 2001 by the NEAR-SHOEMAKER spacecraft, although it was not designed for this [2]. For about twenty-five years, also DLR is involved in the development of dedicated landing systems for small body exploration in various consortiums. Starting with the successfully flown PHILAE lander [3], followed by MASCOT [4] and the most recent MMX Rover IDEFIX [5], the range of developed landing systems breaches from approx. 10 kg up to nearly 100 kg system mass. Of course, not all studied landers were actually launched, some did not even finish phase A and reached a very preliminary development status only.

With a focus on structures, Table 1 lists chronologically landing systems of which the primary structural design was conducted at DLR. Launch dates in brackets indicate landers that did not proceed beyond phase B or are currently still under investigation. A dedicated differentiation is made by the type of structural interface (I/F) to the main (or mother) spacecraft: either the lander is body-mounted, i.e. directly fixed to a space probe's structural panel, or via a dedicated I/F structure between the lander and a space probe's structural panel. Except of the currently ongoing APOSSUM study [19], the heavier landing systems are of body-mounted type, while the lighter ones come with their own interface structure. This means that especially the lander's hold-down and release mechanism (HDRM) is provided as an integral part of the interface structure. With this differentiation made (and again excluding APOSSUM for which also a body-mounted configuration can be though), the small body landers with dedicated interface structure discussed in this paper are: MASCOT, MASCOT2, IDEFIX and MASCOT3. In the following, their system design and some specific features are presented shortly.

MASCOT [4]: The DLR Mobile Asteroid Surface Scout (MASCOT) is an approx. 10kg shoebox-sized lander platform developed for the HAYABUSA2 (HY-2) Asteroid Mission which landed in 2018 on the C-class asteroid (162173) Ryugu (formerly 1999 JU_3). MASCOT carries four scientific instruments as well as a mobility mechanism (mounted on a "common" electronic box) for self-righting and relocation on the asteroid during autonomous operation. The MASCOT system is subdivided in two main structural composite parts, the Landing Module (LM), housing all experiments and sub-systems, and the Mechanical and Electrical Support Structure (MESS). It provides the LM's interface to HAYABUSA2 until separation.

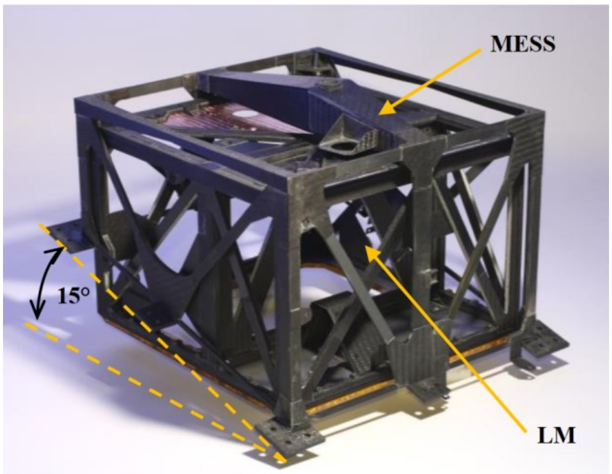


Figure 1. MASCOT LM & MESS FM structures

Table 1: Selection of structural characteristics for small body lander structures developed by DLR. Launch dates in parentheses indicate an "initially planned launch date", i.e. either not launched or not confirmed.

Mission	Lander	Launch	Type of I/F-System	System mass (dry) [kg]	Structural mass, Lander [kg]	Structural mass, I/F-system [kg]	1. EF (system) [Hz]
ROSETTA	PHILAE [3]	2004	Body-mounted	97.6	16.70	8.70*	91.6
Mars Premier	NetLander SurfM [7,8]	(2009)	Body-mounted	69.0	9.67	9.0**	182.0
HAYABUSA2	MASCOT [9]	2014	Ded. I/F-system	11.0	0.81	0.70	125.0
AIM	MASCOT2 [10]	(2020)	Ded. I/F-system	14.6	2.17	0.71	127.0
OKEANOS	Jupiter Trojan asteroid lander [11]	(2024)	Body-mounted	85.3	6.40	---	89.9
MMX	IDEFIX [20]	2026	Ded. I/F-system	23.1	2.96	1.19	122.0
Ramses	MASCOT3	(2028)	Ded. I/F-system	18.5	Comparable to MASCOT2		
Ramses	APOSSUM	(2028)	Ded. I/F-system	84.5	6.90	5.10	116.0

*Mechanical Support System (MSS); ** Spin up and eject device (SED)

MASCOT2 [6]: MASCOT2 was studied as a contribution to ESA's AIM mission concept, heading to the Didymos double asteroid. Being a direct successor of MASCOT, the proposed landing system is quite similar in mass and dimensions to MASCOT. The major changes are the inclusion of a bistatic low frequency radar (LFR) into as primary science payload. Further a few modifications of the MASCOT system address specific AIM mission requirements such as long-term surface operation (≈3 months) by adding solar generators as well as a second mobility mechanism on the common electronic box for improved steerability. The remaining available space is used up by a camera (MasCam) and radiometer (MARA), similar to the ones as flown on MASCOT, and an accelerometer (DACC).

From structural point of view, those changes led to a slightly scaled-up lander unit with shifted payload interface points, but not changing the overall framework design. In contrast, the MESS structure has been completely redesigned. The total mass of the MASCOT2 system (Lander Module, MESS and Payload suite) is less than 15 kg (incl. maturity margin).

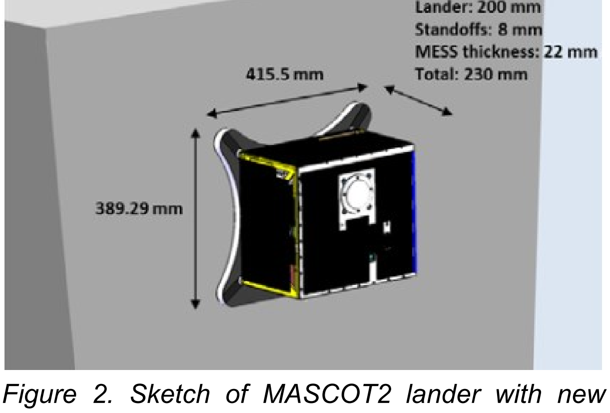


Figure 2. Sketch of MASCOT2 lander with new interface structure when mounted to a S/C panel.

IDEFIX [12,13]: The Rover IDEFIX is a contribution by the German Aerospace Center (DLR) and the Centre National d'Études Spatiales (CNES) to the Japanese Space Agency's (JAXA) Martian Moons eXploration (MMX) mission. With a total system mass of 24.85 kg it is approx. twice as large as MASCOT, but still considered as very compact. While the outer shape remained box-like, the structural design of the lander (Rover) is quite different. It consists of six carbon fibre-reinforced sandwich plates (with aluminium honeycomb core). The so-called MECSS (Mechanical, Electrical and Communication Support System) interface structure is derived from the MASCOT2 one. Once IDEFIX will be delivered to the surface of Phobos it will perform in-situ science and scout the surface by gathering data in order to prepare the landing of the MMX main spacecraft.

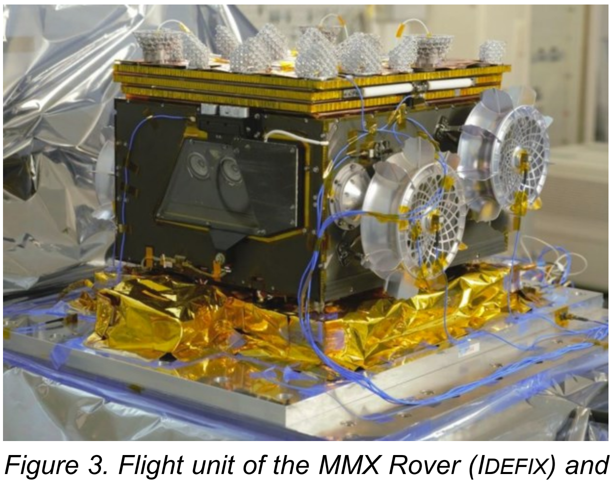


Figure 3. Flight unit of the MMX Rover (IDEFIX) and its interface structure during shaker acceptance test.

MASCOT3 [17]: Currently studied as a contribution for ESA's Rapid Apophis Mission for SpacE Safety (RAMSES) spacecraft, MASCOT-3 is building up on the MASCOT concept. The goal is to re-use as much as possible from still available MASCOT FS (Flight Spare) hardware and swapping in mission-specific new hardware, because of a very tight schedule and to keep costs low. This includes not only scientific payloads, but for example also the common electronic box and the landing module structure, which is supposed to be a 1:1 re-build of MASCOT hardware (at the time of writing still under investigation). Instead of a simple SLI, solar cells and dedicated antennae are covering the exterior. As interface structure, the MASCOT2 design is under consideration. Overall, the design goal for mass, dimension and stiffness is quite similar to MASCOT2.

LANDING MODULE UNITS

The previous section highlighted a few small body landing systems that share a common root with MASCOT. Comparing the numbers listed in Table 1, their envelope, system mass, stiffness and type of interface system are quite similar to each other. They all feature parts with the same or at least a very similar design (e.g. the Push-off mechanism). Other parts saw larger modifications (e.g. the E-Box) and again others were newly introduced (e.g. the interface subsystem and structure, respectively).

The goal of this section is to present the commonalities of the structural design concepts, but also their peculiarities or variations in order to comply with varying mission requirements. For that the focus is on the lander structures first and on the corresponding interface structures after. Further the pros and cons of each design are discussed.

MASCOT landing module

The MASCOT landing module (295 mm x 275 mm x 195 mm, Figure 4) is designed as a classic framework structure based on six separate CFRP/foam sandwich panels. Each sandwich panel is an "2-D in-plane framework" made of 5 mm foam core and unidirectional CFRP (Carbon Fibre-Reinforced Plastic) face sheets. Those "2-D framework panels" are interconnected via dedicated shear straps, thus forming a 3D framework structure. Thus, the structural design makes maximal use of the highly orthotropic material properties. Only the removable radiator plate is designed as an aluminium sandwich structure for thermal reasons, connected via screws to the four "side panels" [9]. Through this design, the structural mass is with 0.70 kg extremely low.

Significant structural loads are introduced close to nodes, wherever possible. Thus, the major payload interfaces as well as the Electronic Box interface are partially dictated by the size of the lander framework and vice versa. In this context, a key element is the central panel, which supports not only the two heaviest payloads but also accepts the central HDRM bolt (cf. Figure 5). This single bolt pulls and releases the lander to and from its interface structure, respectively. Thus, during launch and flight, the lander is under continuous tensions load, which is relieved by a mechanism shortly before deployment. The corresponding reaction forces, introduced by the central HDRM, are borne at four corner points at the lander bottom panel (cf. blue points in Figure 5).

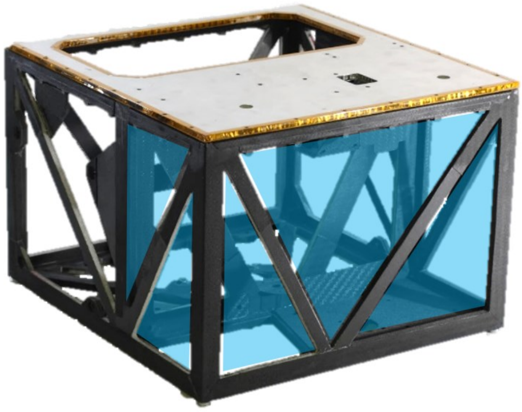
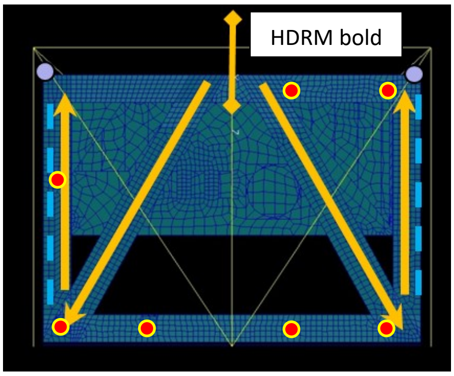


Figure 4. MASCOT landing module. Its payload compartment highlighted in blue.



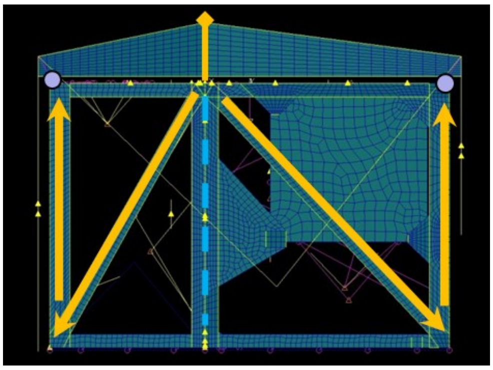


Figure 5. Load path within the lander's framework structure: Section view with load path from NEA through central panel (orange and blue lines) and red marked P/L I/F points (top); side view of landing system structure with load path from lander central plane to the interface structure bearing points (bottom).

The main payload interfaces in the central panel are realized as through holes and their location as close as possible to nodes and out of the load path, respectively. Smaller payloads and subsystems receive a dedicated support platform, which is glued in between the framework struts and allowing more flexibility in the positioning.

MASCOT2 landing module

The MASCOT2 landing module (295 mm x 325 mm x 195 mm) is an up-scaled MASCOT with and additional length of +50 mm, a second mobility mechanism and a partially exchanged payload in accordance with the AIM science mission goals. The extension of 50 mm is added to the so-called Electronic Box compartment (or warm compartment) of the lander. The additional space is needed for a second mobility mechanism and attached to the electronic box (same as the other mobility mechanism). As the dimensions of the electronic box itself roughly remained, the corresponding lander structure's interface points required an adjustment in order to still fit the electronic box interfaces. In contrast, the mechanical interfaces of swapped-in radar electronic box are given the requirement to fit with the already existing structural interface points of the instrument that is replaced. Eventually, the overall structural concept with tits main load paths remained and a finite element simulation showed general feasibility with similar stiffness as for the MASCOT-1 lander.

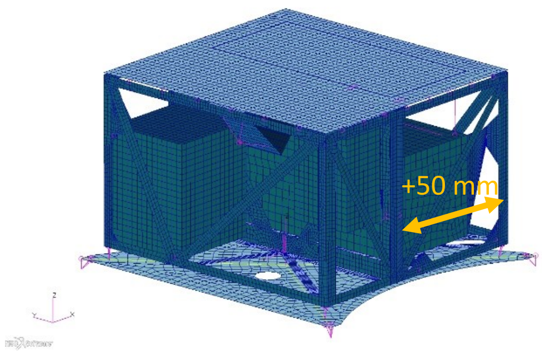


Figure 6: MASCOT2 FE model with an extension of the electronic box compartment (+50 mm) and new interface structure, compared to MASCOT.

IDEFIX Rover (lander)

In the frame of JAXA's MMX mission a wheeled landing module (rover) is provided in a joint DLR-CNES effort. Similar to MASCOT, it is a box-shaped structure, but larger, (376 x 445 x 232) mm³, heavier (23.1 kg system mass) and based on a different structural concept. Instead of a framework structure the Rover structure (in the following called chassis) consists of a half-integral U-shaped base body as depicted in Figure 2. It includes the bottom plate, the left and right side plate as well as a partial top frame serving as harness and MLI bracket. The chassis base body is completed by separable front and rear panels as well as a separate top plate.

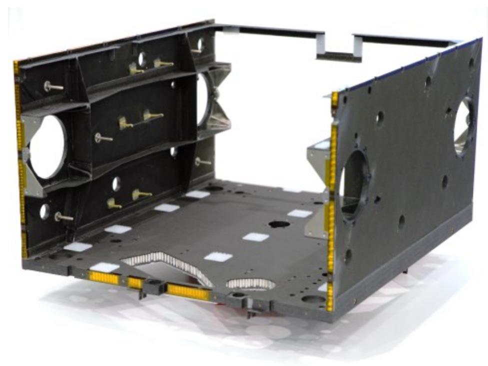


Figure 7. Flight unit of the MMX Rover's chassis base structure.

All plates/panels are made from CFRP sandwich plates with honeycomb core. Screwed interfaces are largely relying on CF-PEEK (carbon-reinforced PEEK) inserts with bronze helicoil threads and titanium screws. The chassis side plate(s) is one of the highest loaded and more complex part in the structure, stiffened with a solid CFRP frame on the inside. This allows to support the four locomotion units including their motors and to transfer loads between the panels. Each side plate carries two fully equipped locomotion units incl. corresponding HDRMs. In addition, also the top plate with one fixed and three deployable solar generators attached is mainly supported by the side plates.

Thus, the side plates are connected rigidly (glued) to the rover bottom plate and distribute loads from the locomotion units into the bottom as well as front and rear panel, respectively. Instead of one central HDRM as for MASCOT and MASCOT2, the rover chassis is connected (at its bottom plate corners) via four HDRMs to its interface structure. This configuration avoids the constant pre-tension present in the lander and interface structure. On the other hand, three additional mechanism are required to keep the rover in place during launch and flight. However, it was also possible to connect the rover full panel chassis with one larger central MASCOT-like HDRM to its interface structure.

MASCOT3 landing module

The structural baseline design of the currently studied MASCOT3 is a 1:1 copy of MASCOT. Actually, the MASCOT3 SM could potentially reuse the still existing MASCOT flight spare structure. The exchange of one of the major MASCOT payloads is realized by adding for MASCOT3 a new payload platform. This is using the existing interface points in the lander's payload compartment and at the same time allowing multiple smaller payloads and subsystems (with quite different mechanical interface points) to be accommodated.

INTERFACE UNITS

After focussing on the lander unit's structure, this section discusses the evolvement of corresponding interface structures in detail. The advantage of a landing system consisting of a lander and a dedicated interface structure (or system) is the limitation of interface constraints with the mother spacecraft. Especially all testing related to the separation event is quite independent from the mother spacecraft. The latter one provides only mechanical and electrical interface points, but no mechanism. Further, the interface system allows to allocate additional sub-systems, for example calibration devices, that are directly and only related to the lander and its payload, respectively.

For clarity, the following interface units' description is sorted in the same order as the corresponding landing module units in the previous section.

MASCOT interface unit (MESS)

Similar to the MASCOT landing module, also the interface structure (MESS – Mechanical and Electrical Support Structure) is a framework design. Unlike the separate 2-D framework elements of the landing module, the MESS features 3 mm thick solid quasi unidirectional CFRP struts. These are again interconnected with shear straps. The main design driver for the very peculiar MESS design is to mount the landing module in an inclined position below the HAYABUSA2 (HY-2) probe's solar generator panels and within the HY-2 backboard panel. For this the MESS is fixed with six foot point brackets to the HY-2 backboard panel. The landing module is supported within the MESS framework at four bearing points in its "upper" corners (cf Figure 8, bottom). Further, on the upper side, the MESS features a central sandwich truss, which houses a non-explosive actuator (NEA), an umbilical connector (UMC) and a spring actuated push-off mechanism (POM) [14]. The central NEA bolt realizes the only "rigid" connection between MESS and LM by pulling it with 2500 N into the aforementioned bearing points.

MASCOT2 interface unit

From MASCOT to MASCOT2 the interface structure is completely re-designed. The purely accommodation-driven MASCOT framework design is replaced be a flat CFRP sandwich structure which simplifies the structure design and build significantly (cf. Figure 9, top). The interfaces towards the mother spacecraft panel and the landing module bearing are located closely to each other, which offers a design challenge and opportunity at the same time (cf. MMX interface structure). Also, there is

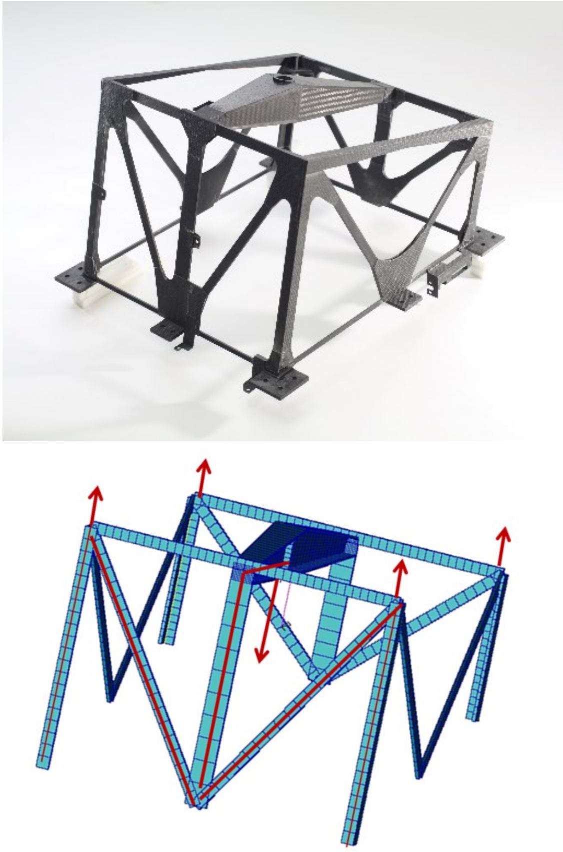


Figure 8. Flight unit of the MASCOT (MESS) interface structure (top); FE model with reaction force vectors at the "upper" corners with landing module cup-cone interfaces (bottom) and a central HDRM bold (see also Figure 5).

no longer the chance that the lander jams within the framework due to an unintended tumbling motion. However, the Hold-Down and release concept with four bearing points in the corners and a central push-off mechanism with the co-linear NEA bolt remains 1:1 the same as for MASCOT. The length of the (MASCOT) push-off mechanism also determines the thickness of the interface structure with an aluminium honeycomb core of 20 mm. Even though simulations show that a thinner aluminium honeycomb core does not alter the system stiffness, maintaining the form factor is chosen over minor mass savings [15]. Removing material and adding a slight curvature at three of the four edges results in much larger mass savings. The mechanical connection of the interface unit to the mother spacecraft is realized by four inserts in the corners. The inserts provide a through hole, thus allowing a fixation of the interface unit to the mother spacecraft panel via four screws.

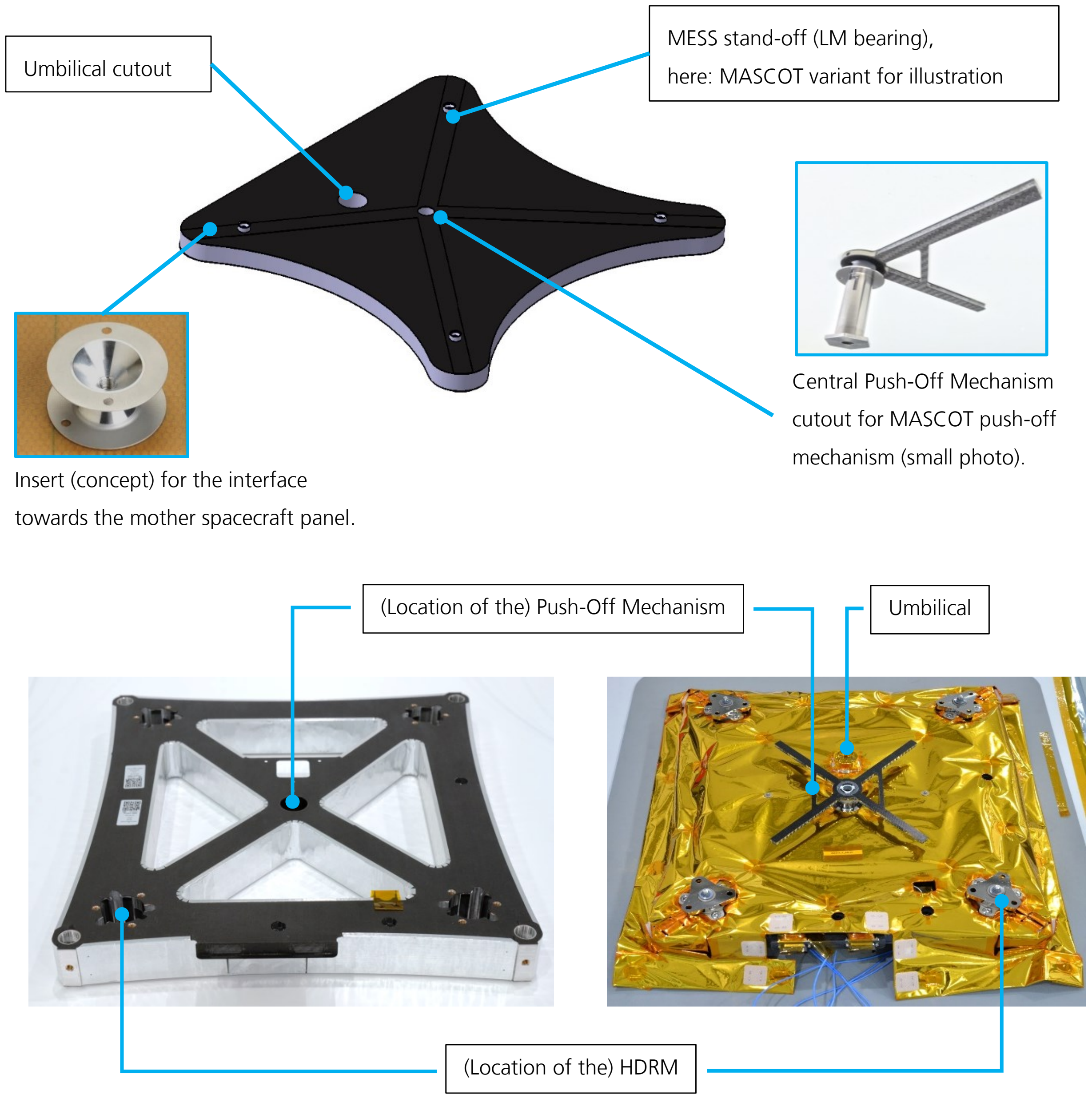


Figure 9: Study of MASCOT2 interface structure (top) and MMX FM interface structure (bottom).

MMX interface unit

The MMX interface unit is based on the MASCOT2 study and, at first glance, seems to have many commonalities with it. The geometry is up-scaled and both structures are designed as an aluminum honeycomb sandwich panel with CFRP face sheets. The MMX interface structure's sandwich panel, assembled from approx. 1 mm CFRP face sheets and a 40 mm aluminium honeycomb core, has additional internal cutouts for mass reduction purposes as well as a slightly bigger curvature at the edges. The push-off mechanism is slightly off-centered due to accommodation constraints (with the umbilical) and features a so-called push-off plate with (2 or 4) arms in order to stabilize the lander unit during its deployment against tumbling. For MMX, the push-off mechanism features a larger (physically and mechanically) spring in order to comply with the increased landing unit's mass and different separation speed to be achieved. The electrical umbilical connector is still located close to the push-off mechanism, also minimizing unintentional tumbling due to the spring-loaded pin contacts [15].

But in detail, there are quite some differences. The most important difference is the configuration of the hold-down and release mechanism. While MASCOT2 maintained the MASCOT configuration with four cup-cone interfaces in the corners and one central non-explosive actuator, the MMX interface unit features four HDRMs in the corners. They are fixed to four larger ALM (Additive Layer Manufacturing) aluminum main inserts which carry the HDRMs and also provide an interface to the mother spacecraft [16]. Thus, there is a quite direct load path between the mother spacecraft panel and the Rover (lander unit).

MASCOT3 interface unit

As the MASCOT3 landing module is thought as a 1:1 copy of MASCOT, the corresponding interface module must feature interfaces that are mechanically and functionally compliant to the MASCOT landing module. This is provided by the MASCOT2 interface module. At the time of writing, the currently studied baseline for the MASCOT3 interface structure's design is a combination of both, the MASCOT2 and the MMX interface structures. From MASCOT2, the HDRM configuration with four cup-cone interfaces in the corners and one central non-explosive actuator, is combined with the basic shape of the MMX interface structure and its ALM corner insert design. The push-off mechanism remains basically the same as used in MASCOT.

A FAMILY CONCEPT FOR SMALL BODY LANDER STRUCTURES

Finally, the discussion is on to what extend the MASCOT landing system's structure and its derivates form a "small body lander family". The idea of a small body lander family with dedicated interface structures is not new. It has been reported for example in [18] how small (body) landers such as MASCOT and derivates can enhance many kinds of exploration missions. However, the focus was not on structures.

Now, with the earlier mentioned MASCOT3 lander for Ramses, another structural derivate of MASCOT is studied. The baseline is to re-use 1:1 the existing lander's structural design and to combine it with a MASCOT2/MMX-like interface structure. Exchanging one of the MASCOT main payloads by multiple smaller units requires a specific multipurpose payload balcony within the payload compartment. Thus, the existing payload interface points of the MASCOT lander are not touched, but additional smaller units can be still accommodated rather flexible. On the other hand, the electronic box and/or the radiator sandwich plate possibly require modified or additional interface points. Both can be easier realized due to the fact that both are aluminium and aluminium sandwich structures, respectively. Those minor (TBC) changes and the "re-use" of the main structures design allow to significantly reduce development time and costs. The primary structure would mostly undergo a delta-qualification only. This is not entirely true for the interface structure, as it combines two earlier designs in one (MASCOT and MASCOT2/MMX). Hence, for the interface structure a delta-qualification is not sufficient, even though the conceptual design is not a new development either. If this interface structure was realized and qualified, another small body (micro) landing system in the range of 10-30 kg and derived from MASCOT would be in existence. In addition, the identified drawback of "fixed" interface points in the lander framework structure will be partially overcome by the addition of a multi-purpose payload platform with variable interface points. Thus, the scalability of the design is further improved.

Also, the evolvement of the structures from MASCOT to MMX and MASCOT3 demonstrates that combining "flexibly" the presented lander and interface structures (with varying HDRM concept) can be thought. For example, an IDEFIX-like structure is compatible with a four-HDRM interface structure, but also a one-HDRM interface structure. The interface structure can be mounted to a flat panel, but also into a pocket and possibly inclined versus a panel. Therefore, we argue that this is the foundation of family concept for small body lander structures.

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