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TECHNOLOGY AND KNOWLEDGE REUSE CONCEPTS TO ENABLE RESPONSIVE NEO CHARACTERIZATION MISSIONS BASED ON THE MASCOT LANDER

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Extended Abstract—

The small asteroid lander MASCOT launched on-board the Japanese HAYABUSA2 asteroid sample-return mission on December 3rd, 2014, was developed and built in a fast paced project under strict constraints of timeline and resources. Tailored model philosophies, standards, and a dynamically adapted test program totaling more than 100 different test campaigns kept project risk under control and compressed hardware integration into 2½ years, barely feasible within a 3-year project even with the benefit of a preceding phase of lander concept studies. These were conducted for various missions and a wide range of lander sizes at the DLR Bremen Concurrent Engineering Facility starting in 2008.

Being a shoebox-sized 10 kg spacecraft, MASCOT carries four asteroid science instruments selected for versatility within the highly intense few hours of its mission on the unknown surface of near-Earth C-type asteroid (162173) 1999 JU_3. Many of its subsystems, especially thermal control, are highly optimized for this target asteroid, but still, first landing site selection may be subject to thermal constraints. Notably, for MASCOT small is not equal to simple: the system's fundamental complexity is comparable to similarly equipped standalone spacecraft and the need to integrate into a smaller volume adds even closer subsystem interdependency. Also structure is “woven in” or organically integrated with subsystems and payloads by providing dedicated modular supports. However, for a very wide range of target objects many subsystems could still be very similar, such as orientation sensors, command and data handling, power distribution, the uprightening and relocation mechanism, and others.

With the lessons learned during the design, integration and management of MASCOT and with the background of an expanding construction set of subsystems in varying states of maturity, the study of derivative systems or "follow-ons" of MASCOT has become more and more self-evident as well as efficient. As far as knowledge and tools concerns, reuse can be made from the series of studies in the DLR Concurrent Engineering Facility (CEF) in Bremen which started off the MASCOT project, as well as the various MASCOT models which were built using Concurrent Assembly, Integration and Verification (AIV) methods. The experience gained in both can be consolidated by Model-Based System Engineering (MBSE) to facilitate future studies and projects. This set of tools becomes particularly useful when small solar system body lander needs to be designed on a compressed timeline. It enables planetary scientists to use flight opportunities that arise late on the timescales of conventional space missions or, as in the case of MASCOT, adapt a design quickly from a discontinued mission to one that goes ahead – or it saves precious lead time when there is the need to meet a specific newly discovered threat.

The paper will show the different aspects of reuse of knowledge and technology in different scenarios and will provide an example for the fictional impactor 2015 PDC by designing a rendezvous and lander mission into the timeframe of the related exercise scenario, at for now fictitious short notice.

I. Types of Reuse

There are several types of reuse known to exist and applicable to a MASCOT-reuse scenario, with definitions mainly stemming from the software product line field of research. In principle, when thinking about knowledge reuse, we can distinguish between two different concepts: the ad-hoc reuse and the strategic reuse, which will be described below:

i) The ad-hoc reuse: Coming from the software engineering, ad-hoc reuse is described by the so-called clone and own approach [1], which is an approach mainly resulting in copying the original design and adapting it manually to the new user scenario. It does not include any kind of change propagation to an original design, much less to a strategically developed platform. One could also apply the (partial) reuse e.g. of an already developed flight model (FM) to fly on a new mission. This path has been taken before, e.g. with the Venus Express mission, which has been partially using the Mars Express flight spare (FS) hardware. [2] The approach comes with benefits with regard to the development of the new mission, e.g. in reducing development time and cost, but is by no means a strategic approach nor a multi-mission scenario, as flight spare models are only a single source. A possible scenario for reusing some of the MASCOT FS hardware in combination with a solar sail is provided in [3], for the sailcraft also cf. [4].

ii) The strategic reuse:

A more strategic reuse of knowledge and design requires more upfront investment. Here we describe two methods for a more planned and enforced reuse, both focusing not only on the reuse of the product itself (as in the ad-hoc reuse scenario), but also the reuse of underlying knowledge and processes in the different stages of the product lifecycle. The first method is the ontology-driven requirements engineering process. In applying an ontology-driven process, the requirements engineering stage can be shortened and improved by improving the requirements quality and completeness. It is also possible to generate generic requirements ontologies for different levels of generalization, which can be applied when starting the development of a new MASCOT mission. This approach has been described by Antonini et al. in [5].

When thinking about levels of system generalization, i.e. going from a specific NEA landing package to a generic small body landing package to a nanoscale (deployable) instrument carrier, the whole potential of MASCOT reuse manifests itself. Strictly thinking this through, there is a high potential of applying the so called product platform approach to MASCOT follow-on missions. This implies a strategic reuse of knowledge and its application not to only one mission but rather to a planned family of missions with planned commonality and variability. It requires strategic variant management and planning ahead, as well as proper knowledge management and management of the system (and domain) engineering artifacts. Tools and methods to do so are being described in chapter III.

Traditionally, product lines or families are displayed and managed along the product features, i.e. observable functionalities of the system. The figure below, a so called feature tree shall provide a first idea about different features and markets that could be realized and attacked by a MASCOT product line. The partial feature tree shows a distinguishing among three major features, i.e. the landing velocity the system can sustain (which comes along with the delivery strategy as imposed by the main-S/C), the lifetime the system can operate on the target surface and the type of batteries which are included. In the feature tree, features or functions can be optional or mandatory, and they can be alternative decisions, i.e. exactly one feature must be selected (like the landing velocity) or so called OR-features, where at least one feature must be selected.

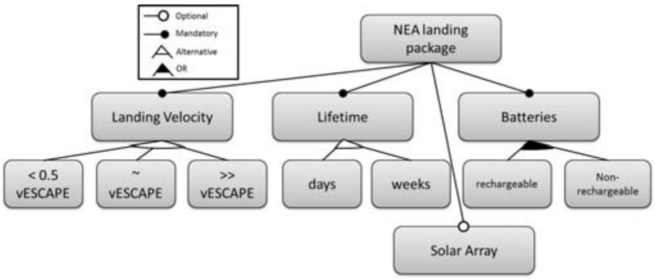

Figure I-1: Example for a (first, incomplete) MASCOT-X feature tree

The upfront investment that is required here is the development and maintenance of a core platform throughout the derived MASCOT-variants and their missions which are most certainly no parallel but offset developments. However, properly applied the approach will provide a reduction in development time and cost for subsequent or multi-mission scenarios.

II. Tools and Methods

For managing the strategic reuse of the MASCOT-knowledge, we are working on different tools and methods, e.g. using the model-based systems engineering approach. For this purpose we have developed MASCOT SysML models incorporating also domain analysis models for quick impact of change analysis. (For further illustration also cf. the poster.)

i) Adaptable Structures and Accommodation

From structural engineering point of view a modular lander is a double-edged approach. Especially the extremely compact framework design of MASCOT was developed around and influenced by the subsystems

and payloads. Hence, scaling the system by geometry, and thus with it the structure, works only if also subsystems and payloads were scaled by the same proportion. In addition to sizing issues this is due to the limited availability of structurally feasible mounting point locations. On the other hand a function-integrated design concept and the box-shaped accommodation concept with a warm and cold compartment allow still some flexibility (see Figure II-1, background). Also the interface structure, which comes with the lander, is adaptable [9].
The function-integrated design concept is further strengthened by the current development of an add-on tool for finite element simulations within the DLR CarboTherm study. The tool will allow a parallel structural-thermal analysis of modular composite structures during Phase-0/A studies and support system engineering and conceptual decisions. For this purpose it is based on a database which includes established, well-known and qualified materials combined into and/or with corresponding design and manufacturing solutions. Especially joints, interfaces and composite build-ups are represented, which are the key elements to describe a structures' thermal conductivity. Further, the rating of a selected design concept with impact factors like thermal conductivity vs. mass, level of manufacturing complexity and maturity et cetera shall be included.

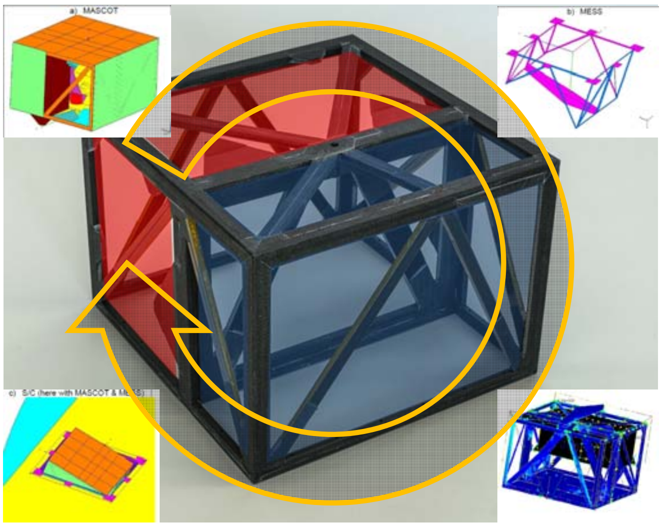

Figure II-1: Modular MASCOT Landing Module with separate warm (red) and cold (blue) compartment. A combined structural-thermal design approach for Phase-0 and –A supports MBSE and system level support.

All together this approach will enable the structural engineer to perform a simplified end-to-end coupled thermal and mechanical systems properties' analysis for scenario-specific boundary conditions (see flow diagram in Figure II-1). This early assessment of the structures' thermal capabilities is very important as with smaller systems the thermal subsystem becomes more and more sensitive to environmental, in particular thermal changes. Hence, the tool supports not only the thermal design engineer but also the system engineer in MBSE and CE studies respectively.

ii) Reusable avionic, scalability and upgradeability

The design of the MASCOT avionics subsystems as such has high potential for reuse and upgradeability as well as a general flexibility (in terms of reuse "as is") to accommodate e.g. changing instruments on the platform. In general it is clear that if ad-hoc re-use is the goal, interfaces may be overconstrained for a new mission and sometimes difficult to implement or at least creative workarounds have to be found to add functionalities missing in the original design. On the other hand, in the case of strategic re-use there is always a tendency to over-generalize interfaces into standards that then carry an overhead of functionality that is unnecessary to a particular mission and thus comes with penalties in terms of mass, volume or energy consumption.

We here pass over the trivial approach of simply re-using still healthy qualification model hardware and/or flight spares in a direct manner and discuss the application of the interfaces to potentially other instruments. For a serious mission development following up a generally successful concept, the most direct approach would be to define the as-built design description of the first entity's spacecraft bus as the interface control document for the instruments of the next. In general, the MASCOT avionics architecture offers slots in a common E-box (see Figure II-2) for instrument back-end electronics as well as subsystem electronics (e.g. GNC sensors and mobility) with defined interfaces to the MASCOT Onboard Computer and PCDU itself.

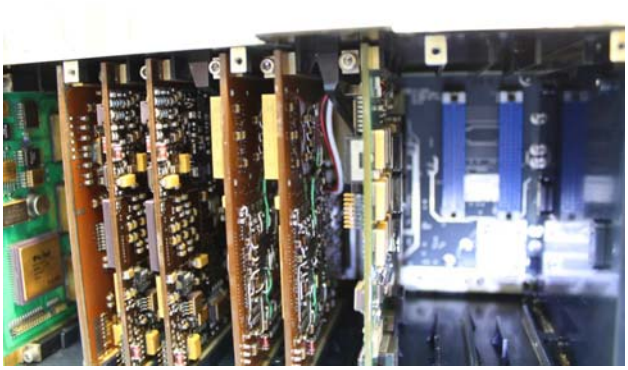

Figure II-2: View into MASCOT E-box with subsystem PCBs and instruments backend-electronics partially integrated

In the MASCOT case (cf. [6] for details of the MASCOT design) those slots are:

- one PCB card module with redundant serial data link, 3-voltage non-isolated supply

- one PCB card module with redundant serial data link, 3-voltage non-isolated supply
- one self-contained instrument with redundant SpaceWire data link, 2-voltage isolated supply
- one instrument of up to two PCBs card modules in the E-Box with redundant SpaceWire data link, 3-voltage isolated supply
- a redundant set of analogue sensor read-out lines and discrete logic command lines directly to the On-Board Computer, with a redundant single-voltage non-isolated supply

If instruments can be designed to meet these interfaces, reuse of the bus can be applied quickly and comes along with time-saving efforts in terms of reduced interface testing. This approach to partially genericized, partially ad-hoc re-use oriented, and partially strategic re-use oriented interface (re-)definition can be used as a tool to tune the development effort and design concept to the science requirements and programmatic realities of follow-on missions and studies, tailoring the development effort to its purpose and environment, and enabling early focus on the hotspots of design change and AIV challenges driven by the new mission. It further

It is also in keeping with the approach of concurrent AIV in the characteristic environment of widely varied maturity levels of the spacecraft units at project start which then have to be lead towards convergence on flight readiness. (cf. [7])

The outlook for participation of small landers and sub-spacecraft accommodated in a main spacecraft as pioneered by Philae [8] and MASCOT is promising. The evolution from HAYABUSA to HAYABUSA2 paved the way for multiple sub-spacecraft concepts. In addition to their use as low-velocity deposited landers as for MASCOT on HAYABUSA2 or PHILAE on ROSETTA [8][10], which could be extended to the AIM component [11] of the joint AIDA mission [12] in the same manner, HAYABUSA2 has also expanded the use of small sub-spacecraft to the observation of dynamic processes with its Small Carry-on Impactor (SCI) and deployable observation camera, DCAM3. [13][14] In a similar manner they may in the future be used in kinetic impact tests such as the DART component [15] of AIDA or the Kinetic Impactor Demonstration Mission proposed in the framework of NEOshield [16] to investigate dynamic phenomena and environments [17][18].

In the past, related missions like e.g. Deep Impact have realized late launch margins in the 10's of kg range despite having been sized to their launch vehicle [19], unlike HAYABUSA2. In this case, it may be possible to fill up the science instrumentation of such missions with the late and dynamic addition of modular sub-spacecraft if the main spacecraft has been prepared for this situation and it was aptly modelled during the previous design phases.

III. POSSIBLE APPLICATION FOR THE FICTIONAL IMPACTOR 2015 PDC

As for the scenario of the fictional impactor 2015 PDC, at the moment both described reuse scenarios are possible, as the MASCOT FS is still available and assembled at the time of this conference. Its design is virtually identical to the MASCOT FM which we describe in another paper at this conference [6]. So the first quick solution would be a modification of the MASCOT FS, which would jump onto an extremely fast paced development and mission timeline (together with the to-be-developed carrier mission), to allow for a first characterization of the PHA. (cf. [3] for a marginal-minimum modification approach) Modifications will be required regarding instrumentation, i.e. to allow for a better adaptation of the measurement scenario to the requirements that stem from a PDC related characterization task. This can be done in a relatively short timeframe of 2 years; an approximated time for modification with other off-the-shelf (OTS) equipment and delta-qualification based on the concurrent AIV experience gained with MASCOT which we describe in another paper at this conference [7].

Given slightly more time, maybe on the order of an additional 2 years, the strategic approach might come in handier, also having in mind either a flight of more than one MASCOT-X-entity on a main carrier, e.g. to perform different tasks previously combined in one lander, [8] or more than one mission to be launched to the target object in subsequent launch window time intervals. This situation can arise if the asteroid predicted to impact Earth cannot be fully characterized in the first mission. Also, post-deflection characterization may be desirable or necessary. If a resonant return of the object having passed through a keyhole is likely, a precision follow-up deflection is required to exclude all predictable impacts. Unless the post-deflection fly-by of Earth is very close, the design driving environments at the target object are unlikely to differ much due to the already high typical eccentricity of asteroid orbits. Then, a maximum re-use for follow-up missions would not just be necessary due to time constraints but also convenient, as it could be for science missions in normal times.

IV. SUMMARY

Reuse of knowledge from the MASCOT project and its application to the PDC context is important and more so in a strategic manner. We have proposed some of the methods and processes that can help to reduce the development time and cost when sending a MASCOT-type nanoscale instrument carrier to a potentially hazardous object. Further analysis of specific designs is provided in other papers for this conference and will be provided in the future. Important is the strategic planning for reuse, as only this provides the essential savings as well as a sustainable development.

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