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# Spacecraft for Hypervelocity Impact Research – An Overview of Capabilities, Constraints and the Challenges of Getting There

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**Abstract**

We present an introductory overview of the capabilities, constraints and challenges to be taken into account in the design of space missions for HVI research and application, focusing on related planetary defence applications, small spacecraft approaches, using our activities and projects as examples. Large lightweight deployable structure applications are discussed, for large-scale photovoltaic arrays in advanced solar-electric propulsion missions, and for solar sailing as a non-fuel-constrained method of achieving high-energy or retrograde orbit and multiple target missions. Small asteroid landers are discussed as vehicles for precursor exploration of impact target asteroids, precision target orbit determination, and for impact process monitoring that also can be deployed from sail-based missions.



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*Keywords*: small spacecraft; planetary defence; asteroid lander; solar sail; high velocity impact

## 1. Introduction

The recent developments in planetary defence following the Chelyabinsk airburst have led to renewed interest in practical asteroid deflection methods based on current technology. The kinetic energy interceptor (KEI), a hypervelocity impact (HVI) application, is a promising mitigation method for small to medium sized asteroids headed for Earth impact with warning times of several years or more. The KEI needs further HVI research to determine the conversion efficiency of impact energy to momentum transfer for various target compositions and structures. Considering the limitations of ground-based facilities, it seems possible that space-based experiments can widen the accessible parameter space for basic research.

Spacecraft entered the realm of active experimental HVI studies on July 4th, 2005 with the DEEP IMPACT impactor successfully autoguiding into the nucleus of comet 9P/Tempel (Tempel 1) at 10.3 km/s relative velocity. The impactor mainly took images of the 7.6 · 4.9 km nucleus which were recorded for re-transmission to Earth by the main spacecraft flying by safely at a minimum distance of 500 km. Because the success of one mission goal – dust cloud generation – was spectacularly achieved, the other mission goal – imaging the crater – could not be achieved immediately by the main spacecraft in its fast fly-by [1]. While observations of the comet materials in the dust cloud were highly successful, phenomena related to the impact process could only be observed from distances larger than 700 km at a resolution of 2 μrad in panchromatic images taken every few seconds [2]. Confirmation of the creation of an artificial impact crater by imagery had to wait for another fly-by of 9P/Tempel in 2011, by NExT, the re-purposed STARDUST spacecraft. The crater generated

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by DEEP IMPACT had a diameter of 150 m and was about 30 m deep with a central mound likely of fall-back material almost completely filling the cavity [3]. STARDUST had previously visited comet 81P/Wild (Wild 2) in 2004 to collect dust samples. Particles in the µm range were caught during this fly-by to within 234 km of Wild 2 at 6.1 km/s by an aerogel target [4] which was returned to Earth by capsule in 2006 during the fastest re-entry of an artificial object at 12.9 km/s. [5] Although planetary (re-)entries into exponentially dense atmospheres have been flown at entry velocities from about 5 km/s at Mars or Titan [6] to the 47.8 km/s of the Galileo Probe capsule at Jupiter, these are not sudden interactions of two colliding solid bodies. Impact, demanding on the design of a spacecraft though simple in principle as a landing method, has remained the exception; where (or rather, when) it was used successfully, destruction of the spacecraft was accepted and the approach velocity was kept to the minimum to maximize data taking time for the mission's planetary science objectives. [7]

## 2. Planetary Defence Background – Target NEO instead of Target Earth

The widely reported and just barely non-lethal atmospheric entry of the Chelyabinsk bolide on February 15th, 2013, returned the focus on planetary defence (PD). In the aftermath of this event, the size-frequency distribution of natural impactors at Earth and their potential for destructive effects on the ground, and technical options for NEO deflection were revisited extensively [8]. The first wave of attention to the NEO threat had earlier recognized the rare but potentially globally catastrophic impacts of km-scale asteroids (NEA) based on the observations of early photographic astronomical surveys. It drew strongly on prehistoric [9] and historical data [10]. This was formalized into the goal to discover 90% of all NEAs larger than 1 km diameter, relatively quickly followed up by the definition of Potentially Hazardous Asteroids (PHA) of at least 140 m diameter which can approach Earth to within 0.05 AU. The ongoing dedicated NEO surveys based on mass automatic exposure and processing of CCD images [11] confirmed the significant contribution to the threat of the much more frequent small impactors with regional or locally devastating effects [12]. NEAs in the sub-PHA size range have recently become accessible enough to observation to enable estimates of the population based on re-discovery rates which indicate that their relative frequency is somewhat higher than expected from earlier extrapolations down from the PHA size range [13]. Also, modelling of the effects of atmospheric entry and asteroid fragmentation strongly suggests much higher yield to ground-level damage efficiency than previously expected from observations made e.g. at the 1908 Tunguska impact site. [14,15] The shift of focus towards the threat posed by smaller, more frequent impactors also changed the approach towards deflection. Although the distribution of encounter velocities is very similar for all sizes of NEAs, the impulse necessary to deflect an object on a given orbit to a safe passage of Earth reduces with its mass – a substantial reduction of requirements for the expected likely next event: The now become unlikely case of a surprise civilization killer asteroid was replaced by impacts just slightly too large to be dealt with by practical application of preparedness and civil defence infrastructures but likely to occur on human timescales. For yet smaller impactors, the choice is to stand and stare or duck and cover. This made deflection feasible within the present capabilities of the Earth's spaceflight infrastructure. The vast improvements in the global NEO observation and tracking capabilities created in the same period have greatly increased the likely lead time at which a reliable positive prediction of impact can be made; cf. [16] and ref. therein. Early PD scenarios envisaged nuclear payloads of unprecedented size to be put on the largest launch vehicles ever built – and long since decommissioned – for launch on very short warning lead times [17]. Now, derivates of already flown and currently developing interplanetary missions, some of which are discussed briefly below, can meet deflection requirements on timelines of several years to a few decades from discovery to effects application. Advanced methods of deflection are being discussed, e.g. [18,19,20]. Liberated from the non-technical burdens of nuclear solutions and the justified concerns regarding their realization (cf. [21]), it is possible to apply these planetary defence related technologies also for the research of HVI where the expense of going into deep space is justified by the wider capabilities offered.

## 3. Solar System Exploration Background – Eggs and Baskets

After the era of first exploration of our Solar System when early spacecraft were expected to fail and were thus flown frequently and in pairs, there was a transition to rare, large, single spacecraft missions in the late 1970s. Consequently, failures became rare and costly in financial and programmatic as well as scientists' and engineers' career lifetime terms. The resulting stagnation of active experience produces a conservative regulated environment of standardization and processes which keeps success rates as high as the time and budget required to build and fly such spacecraft. Since the 1990s this trend has, if not reversed, then at least mainly due to waning interest and resulting budgetary restrictions left some space for smaller, faster and cheaper missions; adjectives not to be confused with simple or crude. Small missions are fundamentally as complex as their larger predecessors with similar scientific purpose; they require roughly the same development effort for the same tasks, sometimes significantly more just to stay small and earn the reward of affordable facilities, launchers, and most of all, a thoroughly optimized and rigorously understood system. Alternative propulsion methods, i.e. any other than storable chemical propellant based thrusters and the use of planetary gravity assists, are only slowly and 'from below' entering the segment of science missions. They are primarily used on technology demonstration missions adapted to a planetary science objective: Here, small spacecraft are already now the driver of development. Early examples were the 373 kg DEEP SPACE 1 (DS1) which visited asteroid (9969) Braille and comet 19P/Borelly using solar-electric ion propulsion of 2.1 kW power [22,23,24]; the 367 kg European Moon probe SMART-1 which used a solar-electric Hall effect thruster of 1.2 kW to raise its orbit from the initial geostationary transfer orbit (GTO) to capture into lunar polar orbit [25]; and the first successful asteroid sample return by the 510 kg Japanese probe HAYABUSA using solar-electric xenon ion engines [26]. For the largest science missions, the transition towards electric propulsion is only beginning – 56% of the launch mass of the CASSINI-HUYGENS and MESSENGER spacecraft, each, was chemical propellant, but only 34% of BEPICOLOMBO is propellant, of which more than half is xenon for solar-electric propulsion. [27] The obvious next step is the use of large-area structures, either to generate more photovoltaic power for solar-electric propulsion or to be employed directly as solar sails and do away with fuel constraints. A solar power sail has been proposed by JAXA for a Trojan asteroid sample-return mission [28,29] on the basis of the successful solar sail demonstrator IKAROS launched as a secondary payload with the Venus probe Akatsuki. [30,31] IKAROS also served as launcher ballast mass (*sic*!) and was thus not mass optimized.

## 4. Mission Scenarios to Support HVI Research

In the following, we provide an overview of projects, studies and mission scenarios that show potential uses for HVI research and related experiments in space.

### *4.1. "So hoist the foil and booms…"* – from Huge Photovoltaic Arrays to the GOSSAMER Solar Sail Roadmap*

The impact velocities that can be achieved for macroscopic objects are limited by the performance of chemical propellants, electrical power handling capability and air drag on Earth. Similarly, the performance of chemical and electrical propulsion of spacecraft limits the accessibility of small solar system bodies (SSSB) unless gravity assists on major planets are possible and the associated long cruise flight times acceptable. Solar sails are expected to be capable of achieving velocities far beyond those commonly feasible for traditional space missions, which would enable access to many more SSSB targets. They could also enable collision experiments at relative velocities far beyond those currently achievable on Earth. Several solar sail experiments have been flown or are nearing flight hardware status. [28,30,31] Some of us work on the GOSSAMER-1 large lightweight structures and solar sail deployment demonstrator which is in the advanced stages of development at DLR. In its solar sail application it is the first step in the DLR-ESTEC GOSSAMER Roadmap for the development of solar sail technology, leading to practical sailcraft of sizes enabling unique science missions that are presently exceedingly difficult to achieve or not feasible using other post-launch propulsion methods. Among these mission types, three were selected for detailed study as promising candidates for a first science mission using the expected technolgy and maturity level to result from the GOSSAMER Roadmap, on the basis that they are for the foreseeable future only feasibile by solar sail: A multiple NEO rendezvous mission with the capability of additional fly-bys between stays at 3 NEAs within 10 years of flight time [32]; a displaced-L1 spaceweather mission which bears some similarity with an Earth-co-orbital NEA rendezvous flight profile [33]; and a solar polar orbiter mission which bears some similarity with a highly inclined and eccentric orbit NEA rendezvous flight profile [34]. All these missions are small spacecraft in the 100…500 kg range that could ride as secondary passengers to Geostationary Transfer Orbit (GTO) or higher orbits and proceed from there on sail thrust and an optional small kickstage to reduce exposure to the radiation belts of Earth. They are all within the capabilities of currently available sail film and boom technology hardware. One advantage of solar sail as a propulsion method in particular relevant to the multiple NEO rendezvous mission is the relative ease of target object change during the mission. It would for example be possible to re-direct a mission similar to [32] *after* launch to a newly discovered target of urgent interest or change the priority of target objects when the progress of science or other missions makes this desirable. Some flexibility of this kind is, within the limits of carried fuel and photovoltaic power, also possible for some lightweight solar-electric missions, as was shown e.g. by the target object changes of DEEP SPACE 1 throughout its project and flight history. Also, the adaptation of the cruise trajectories of HAYABUSA to and from (25143) Itokawa was only possible due to advanced propulsion capabilities, as is the double rendezvous of DAWN with the two largest main belt asteroids, (4) Vesta and (1) Ceres. For future solar-electric propulsion missions, the Huge Photovoltaic Array technology allows a significant improvement of the electrical power to weight ratio. In the extreme, the spacecraft can be dominated by a solar power sail structure, e.g. [29,31].

Although no specific mission analysis could be undertaken within the scope of this introductory presentation, it may however be assumed that any instantaneous heliocentric orbit reached during the constantly evolving low-thrust trajectories presented in these and other low-thrust propulsion interplanetary mission studies may be taken as the orbit of a NEO to rendezvous with or may intersect the orbit of a NEO to be studied in fast fly-by or to be impacted. Solar sails, which are in principle not limited by propellant supplies, can within realistic mission durations and within the limts of present spacecraft technology development attain fully retrograde orbits. These seem suitable for head-on collisions with objects also within the Earth's orbit, putting within reach encounter velocities in excess of 75 km/s for objects larger than 100 kg [35,36,37]. Although terminal guidance at closing speeds beyond several km/s certainly is a formidable challenge [38,39,40], it seems quite possible, particularly when cooperative targets are considered.

### *4.2. MASCOT – ground truth from a small asteroid lander*

The study of HVI processes requires measurements close to highly energetic events which are inherently dangerous. The Japanese HAYABUSA missions use small landers to help explore their target asteroids, and there have been previous attempts to use small landers for the exploration of small objects in the solar system, e.g. by the FOBOS missions to Mars' moon Phobos. Some of us work on the Mobile Asteroid Surface Scout, MASCOT, which has in the past 3 years been developed by DLR and CNES for a flight opportunity on HAYABUSA-2, after 4 years of more generic small SSSB lander studies. The MASCOT asteroid lander packs four full-scale science instruments and relocation capability into a shoebox-sized 10 kg spacecraft, a lander on the scale of a typical science instrument for a typical interplanetary mission. The Flight Model (FM) delivered to JAXA in June 2014 was launched aboard the HAYABUSA-2 space probe on December 3rd, 2014, and appeared in good health at its first power-up 2 weeks later. HAYABUSA-2 is carrying MASCOT along to asteroid (162173) 1999 $JU_3$ using solar-electric propulsion. MASCOT, following constraints set by its mothership and target asteroid, is an organically integrated high-density design [41,42,43,44]. Main MASCOT subsystem features are as follows: *Structure*: The MASCOT structure is a highly integrated and ultra-lightweight truss-frame made from a CFRP and Rohacell® foam sandwich. *Mechanisms*: MASCOT has three internal mechanisms: (i) the preload release mechanism to release the preload in the structure across the separation mechanism interface; (ii) the separation mechanism to realize the push-off of MASCOT out of the Mechanical Support Structure, MESS, recessed inside the HAYABUSA-2 envelope; and (iii) the mobility mechanism for uprighting and hopping. *Thermal*: MASCOT uses a semi-passive thermal control concept, with two heatpipes, a radiator, and Multi-Layer Insulation for heat rejection during active phases, supported by a heater for thermal control of the battery and the main electronics during passive phases. *Power*: MASCOT is using a primary battery for the power supply during its on-asteroid operational phase. During cruise, it is supplied by HAYABUSA-2. *Communication*: All housekeeping and scientific data is sent to Earth via a relay link with the HAYABUSA-2 main spacecraft. The link is set up using a redundant omnidirectional UHF-Band transceiver and two patch antennae, one on each side of the lander. *On-Board Computer*: The MASCOT OBC is a redundant system providing data storage, instrument interfacing, command and data handling, as well as autonomous surface operation functions. *Attitude Determination*: The knowledge of the lander's attitude on the asteroid is key to the success of its uprighting and hopping function. The attitude is determined by a threefold set of sensors: optical distance sensors, photo electric cells and thermal sensors.

Looking at the worldwide PD and science-related planning for missions to small bodies in the next years, it is inherent that future flight opportunities will arise for such a small versatile add-on landing package which has the capability to complement, complete and counterbalance the main mission's objectives at a comparably low cost. This is why at DLR, we are using our knowledge [45] to build on this heritage by carrying forward the idea of further MASCOT derivatives. Such derivatives or variants will differ in their main features such as lifetime (long-lived vs. short-lived), survivable landing velocity (small or high velocity landing, with or without crushable shells) or instrument suite (e.g. radar tomography vs. geology vs. geochemistry), but will all be based on a common platform. The main goal is to advance the current design from the dedicated lander MASCOT, to a generic instrument carrier able to deliver a variety of science payload combinations on different mother-missions to different target bodies. To minimize the effort of redevelopment and the time to obtain a new design, we are employing principles of Model Based Systems Engineering (MBSE) [46] and Concurrent Engineering. Small landers can also serve to explore the interior of small bodies, e.g. [47]. Particularly when deployed in numbers, they can be used to explore environments too dangerous for the main spacecraft to encounter directly. Jump capability enables the well-timed study of impact effects off the target surface in open space, e.g. the dust and gas composition within the ejecta cone.

### *4.3. PHILAE – Insights at the Heart of a Comet*

ROSETTA is a Cornerstone Mission of the previous Horizon 2000 ESA Programme. The mission was launched in 2004 and reached its target, comet 67P/Churyumov-Gerasimenko in 2014. [48,49] After an intense phase of remote investigation of the comet nucleus including the selection of an appropriate and safe landing site, Agilkia, during the summer of 2014, the ROSETTA Lander, PHILAE, performed the first ever landing on the surface of a comet on November 12th, 2014. [50] It has an overall mass of about 98 kg, including 26.7 kg of science payload, and 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. During cruise the Lander was attached to the Orbiter with a Mechanical Support System (MSS) which also includes the push off device that separated PHILAE from the Orbiter. The selected landing scenario foresaw separation at an altitude of 22.5 km. The descent to the surface took 7 hours, as expected. At touch-down anchoring harpoons were to be fired and a cold gas system should have prevented re-bouncing [51] but failed. During a first scientific sequence of 57 hours while PHILAE was powered mostly by its primary batteries, several instruments and subsystems were operated simultaneously. Each experiment was operated at least once. In the expected long term operations phase the experiments should work mainly in sequence. Data evaluation will then be carried out primarily offline, while preplanning activities are performed in parallel. Lander experiment operations are expected to last up to a few months on the comet surface. In a historical sidenote, PHILAE, for a long time merely known as ROLAND, the ROSETTA Lander, was resurrected as an instrument proposal for the orbiter by a grassroots movement of interested scientists and engineers, after being descoped from the mission following the earlier deletion of an even more ambitious sample return option. This represents the first time that a lander, though in itself a complete spacecraft, is *not* the driving element of the main mission. The concept of integrating a small spacecraft style lander at the instrument level of the mothership mission has since been repeated by the unfortunately lost BEAGLE 2 on MARSEXPRESS, and the target markers, various MINERVAs and MASCOT on the HAYABUSA missions.

### *4.4. AIDA – Together for a Twin*

The Asteroid Impact & Deflection Assessment (AIDA) mission will be the first space experiment to demonstrate asteroid impact hazard mitigation by using a kinetic impactor to deflect an asteroid. AIDA is a joint NASA-ESA mission in pre-Phase A study, which includes the NASA Double Asteroid Redirection Test (DART) mission and the ESA Asteroid Impact Monitor (AIM) rendezvous mission. The primary goals of AIDA are first to test our ability to impact a small near-Earth asteroid by a hypervelocity projectile and second to measure and characterize the deflection caused by the impact. The AIDA target will be the binary asteroid (65803) Didymos, with the deflection experiment to occur in October, 2022. The DART impact on the secondary member of the binary at ~6 km/s will alter the binary orbit period, which can be measured by Earth-based observatories. The AIM spacecraft will monitor results of the impact in situ at Didymos. AIDA will return fundamental new information on the mechanical response and impact cratering process at real asteroid scales, and consequently on the collisional evolution of asteroids with implications for planetary defense, human spaceflight, and near-Earth object science and resource utilization. The AIM component of AIDA has also been studied in variations of spacecraft and science payload sizes for different classes of launch vehicles. These enable accommodation of landers on instrument level in a size range approximately between MASCOT and PHILAE. [52] In the latter's mass and envelope a number of smaller landers could be carried as an alternative concept to cover both bodies of the binary at several landing sites, each.

### *4.5. Fast fly-by study, kinetic impactor, and a brief but complete experience – ASTEROIDSQUADS/iSSB*

A prime candidate method for NEO deflection are kinetic impactors in which a fast fly-by trajectory geometry is modified into a direct hit that transfers to the target all carried momentum of the spacecraft and adds to this that of the ejecta which are generated by the impact energy. In the deflection application in planetary defence, the resulting velocity change of the target, though small, can accumulate into a safe miss distance in the time between the kinetic impactor's hit and the object's close encounter with Earth. The efficiency of the conversion of impact energy to ejecta momentum is to a large extent uncertain. To reduce this uncertainty, various practical experiments and HAIV space mission scenarios [39] have been proposed, including the DART component of AIDA [52]. In an ad-hoc effort for the 2011 Planetary Defence Conference, some of us participated in a distributed concurrent engineering study of a PHA multiple flyby/impact mission concept. It combines a heavy lauch vehicle test as an affordable launch opportunity with a concerted practical exercise of the NEO observation and interplanetary spaceflight infrastructure, from simulated threat discovery to mitigation, optionally including a civil defence response coordination exercise. In this concept, the timing of the launch vehicle test with its expectable delays replaces the coincidence of discovery of a genuine threat and drives the selection of a target object at relatively short notice. This target to which an already prepared mission having to fly with built hardware has to adapt then introduces into its operation real uncertainties and constraints as could be expected from a newly discovered object on which knowledge grows from nil. The mission scenario was restricted to operations relatively close to Earth to minimize mission duration, spacecraft lifetime and infrastructure requirements for the flotilla of several to tens of largely identical spacecraft to be simultaneously operated. It used extremely high data rate transmission to provide target imagery until impact in a scenario of data store-forward relay by two or several of the small impactors in their final approach on the target [21]. The same infrastructure could support instruments studying collision processes after first contact on a timescale of order spacecraft length / relative velocity, m / km/s ~ ms. Such instrumentation, albeit for now with much slower readout, is being developed at DLR for the study of space debris impacts on Earth-orbiting spacecraft. [53] The integration of such a practical deflection experiment with the ground-based planetary defence infrastructures and would certainly serve to develop and inform global and local decisionmaking processes [54] and promote the further refinement of related tools [55].

## 5. Getting There – the Small Spacecraft Approach

Recent interplanetary missions have brought developments that favour small spacecraft. But small spacecraft also pose their own unique challenges, some resulting from the opportunities that uniquely present themselves to them, others from the common misunderstanding that size matters in terms of the effort required or total cost of ownership.

### *5.1. A little Far Out – Small & Secondary Payload Launch Options& Capabilities to Earth Escape*

Many launch vehicles have a minimum payload weight that is due to the advances in spacecraft miniaturization no longer filled by smaller interplanetary missions. For example, IKAROS was added as ballast to achieve the minimum lauch mass of the H-IIA launch vehicle of the Japanese Venus probe AKATSUKI, and was therefore not mass-optimized. [28,30,31] Additionally, one interplanetary and three Earth-orbiting cubesats were carried. Future launches may follow the same concept and have 'live' ballast added in the form of secondary passengers that go along into the escape trajectory, as in the case of HAYABUSA-2. This trend will likely offer affordable launch opportunities also to small interplanetary missions as those discussed above, though under similar constraints as for secondary passengers to Earth orbit. It will pose significant time constraints, physical size constraints, and AIV challenges to these projects which will be highly unusual to the established interplanetary missions and science community, but have been mastered in the course of PHILAE and MASCOT.

### *5.2. Here and Now – the Challenges of Assembly, Integration, and Test and Verification*

The Assembly, Integration and Test/Verification (AIT/AIV) is the final stage in producing a spacecraft and readying it for launch. It includes the simulation and test of the expected space environment and flight operation to verify and demonstrate the overall performance and reliability of the flight system. Choosing the right philosophy or approach of the Verification and Validation process is crucial and driven by risk tolerance. Less verification implies but does not necessarily create more risk. More verification implies but does not guarantee less risk [56]. The classical verification approach (Prototype Approach) which evolves in a mostly sequential and also successive fashion would be of course the most reliable method to choose as it gives the highest confidence that the final product performs well in all aspects of the mission [57]. However, if the schedule is heavily constrained in time, this extensive and time consuming method cannot be applied. On the other hand, the Protoflight Approach, where a single flight model is tested with replacing critical subsystems during the integration process, is also not applicable, since it is very likely that the chosen payloads and the system itself have very heterogeneous maturity levels. Hence, the test philosophy will lead to a Hybrid Approach with a mixture of conventional and tailored model strategies. This approach is common practice in scientific robotic missions [56] but it can be maximized for effectivity and time even further. The project can start with a baseline on the classical sequential approach to ensure a minimum number of physical models required to achieve confidence in the product verification with the shortest planning and a suitable weighing of costs and risks. But this approach can be adapted on a case by case scenario, where the model philosophy evolves along the verification and test process depending on the particular system and subsystem readiness. This includes test models reorganization, refurbishing and re-assigning previous models for other verification tasks if appropriate, skipping test cases, parallel testing of similar or equal models and for some components allowing the qualification on system level. More specifically, parallelization of testing activities using identical copies and flexibility in the model philosophy will create independent unique test threads only joining their dependencies at key points where optional other roads could be chosen. Like Concurrent Engineering, a methodology based on the parallelization of engineering tasks nowadays used for optimizing and shorten design cycles in early project phases, the term "Concurrent AIV" has recently been introduced to express many simultaneous running test and verification activities [45]. In effect, the development, test and verification track of Software Development, Functional Testing, Mechanical AIV and Thermal AIV can get their own independent routes sharing their verification processes. Almost all environmental and functional tests with subsystems can be performed on EM and STM level before the QM and FM are fully assembled which effectively reduced potential delays. In addition, the development of the onboard software including individual instrument and subsystem software, can be performed completely independent with first simulated payloads and later with real hardware-in-the-loop electronic when they become available. This way, every payload and subsystem can freely do debugging tests which can take longer time independently. With this approach, most of the problems for the interfaces and functionality of each subsystem can be found before FM integration. The challenges in creating parallel development lines are found in team and facility resources if these are not readily and on-demand available. The key is to identify test dependencies, test sequences and which test could be performed in parallel. This philosophy is also more complex as it requires overview of the development process of the mother spacecraft, the ongoing progress on system level as well as insight in all payloads and subsystems. It may sound unreasonable to perform the development of a spacecraft in such a manner, whereas well established methods form a "standard way". But if a project is left with no choice of having the luxury of excessive testing, such an approach may be the only option. That this method is not just a theory can be seen in the DLR MASCOT project, a fast paced and high performance deep space project. With a model philosophy tailored 'live' at system level it integrates a unique mix of conventional and tailored model philosophies at units level. A dynamically adapted test programme, limited by a fixed launch date, enabled the shortest planning and suitable weighing of cost and risk. Using Concurrent AIV to identify design and manufacturing issues shortened the project timeline further and kept it at an acceptable risk. In effect, a typical 4 to 5 year system-level AIV phase was reduced to 2½ years. Within these, from the start with the first breadboard model, the MASCOT team has successfully completed approx. 30 MASCOT system level tests, including Shock and Vibration, Thermal Vacuum, Full System Functional, EMC and Integration campaigns. On HAYABUSA-2 it has completed another approx. 10 test campaigns for Sinusoidal Vibration, Mass Balance, Acoustic Vibration, Thermal Vacuum and System End-to-End tests. To develop the MASCOT system and make it flight ready more than 50 additional System Unit tests were performed, excluding any performed by the Payloads or other subsystems provided by the collaborating partners. This culminates in more than 100 different test campaigns performed in roughly half the time usually allocated for such a prototype project which would follow a standardized way, and testing for operations planning continues on spare models.

## 6. Summary

Using missions and projects in which we are involved as examples we provided an overview of the capabilities, constraints and challenges of small spacecraft designs which we consider to have the potential of supporting HVI research and application. We hope that the experiences and lessons learned from these studies and projects and relevant similar efforts accessible from the references below can provide a useful primer for the conceptual design of spacecraft for research ranging from basic HVI phenomena to planetary defence application.

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