IAC-17-D1.2.3

iBOSS Modular Plug & Play - Standardized Building Block Solutions for Future Space Systems Enhancing Capabilities and Flexibility, Design, Architecture and Operations

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Abstract

Modular concepts and standardization of space infrastructure elements have been investigated for decades, while building block systems and standard interfaces have not become reality or routine in space system design yet. iBOSS goes back to a collaborative research project funded by the German Aerospace Centre DLR Space Administration since 2010. While the project name iBOSS - “Intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly” - anticipates solutions for OOS and OOA, the technologies developed provide solutions and enabling features of much broader scope and thereby take mission architecture and space system design to a next level in multiple ways. iBOSS core technology ground qualification in 2017 and 2018 will be followed by envisaged in-orbit demonstration (IOD) in 2020 paving the way for in-space utilization in multiple projects and systems in the 2020ies. The iBOSS GmbH is the catalyst driving the introduction of iBOSS standards and supporting the initiation of multiple partnerships with industry, academia and agencies in a new and unique open-source-type approach.

The paper addresses relevant needs met by modularity and standards, hence plug & play (PnP) approaches followed by a brief description of selected key iBOSS products. However, the paper’s focus is on their application and potential for future space systems both orbital and planetary, i.e. assembly, coupling and servicing or reconfiguration options, hosted payload and facilitated experimental environments. More- over, schemes for iBOSS utilization via new business models and international partnerships as well as a long-term outlook are presented.

Backgrounds of the findings presented are combined experiences made by the authors over decades of involvement in space systems engineering and projects, robotics and simulation, commercialization and new approaches to modular concepts. Partnerships with industry and academia around the world are envisaged for the years ahead.

Keywords: iBOSS, iBOSS GmbH, iSSI, iBLOCK, iSAT, iCASD, VTi, FTI, standard, modular, building block, plug & play (PnP), enabling technology, on-orbit servicing (OOS), intelligent, flexibility, business model, licensing, new systems, efficiency, economy of scale, iBOSS GmbH

Acronyms/Abbreviations

AIT: assembly, integration and testing
BMWi: German Federal Ministry of Economics and Technology
DLR: The German Aerospace Centre
FTI: Fluid Transfer Interface
iBLOCK: intelligent Functional Building Block
iBOSS GmbH: THE iBOSS commercialization entity
iBOSS: intelligent Building Blocks for On-orbit Satellite Servicing and assembly
iCASD: intelligent Computer Aided Satellite Design (tool)
ICU: interface control unit
IOD: in-orbit demonstration
iSAT: iBOSS-based satellite, fully modular composed of iBLOCKs or partly modular as hybrid solution enhanced by iBLOCKs
iSSI: intelligent Space System Interface
OBDH: On-Board Data Handling
OOA: On-Orbit Assembly
OOM: On-Orbit Manufacturing
OOS: On-Orbit Servicing
PnP: Plug & Play
VTi: Virtual Testbed iBOSS (full simulation tool)

1. Introduction

The paper outlines generic considerations associated with OOS and is a combination of background, rationale, technical concept, technical details of selected core technologies as well as an introduction of new collaboration models and technology implementation related to OOS, focused on iBOSS and its issues.

The overall rationale and details as well as an overview video can be visited at the joint iBOSS project website (www.iboss-satellites.com). Moreover, iBOSS technologies represent game changing potential regarding flexibility, design and operations of future space infrastructure elements, but also have an impact on cost drivers as e.g. AIT, and due to higher anticipated lot sizes bring economy-of-scale effects along as well.

iBOSS GmbH (www.iboss.space) is part of a new genre of next-gen industry promoting breakthrough technology capabilities in different business models based on partnership across the industry.

2. Background on OOS and iBOSS Rationale

In the first step OOS has been promoted primarily by the space roboticists community and related activities were for a long time solely focused on technology issues [1]. DLR started OOS-related activities in the late 1990ies following successful robotic experiments as e.g. ROTEX in the course of the Spacelab mission D-2 and ETS-VII with Japan. Initial activities addressed potential future markets assuming cooperative design principles enabling for fully-fledged servicing of satellites. Around the same timeframe DLR and CSA signed an MOU for collaborating in space robotics. A prominent mission proposal at the time was TECSAS aiming at in-orbit demonstration of relevant robotics technologies by two spacecrafts to conduct generic servicing actions and to re-enter the atmosphere as compound object. Similar ambitions by Russia, Japan, Canada and the US led to greater attention of the topic of OOS. DLR, together with CSA and JAXA launched several concomitant activities to more broadly asses and to promote further OOS as well as to build a dedicated community at international level. In 2002 (in Bonn, Germany) and in 2004 (in Vancouver, Canada) international hands-on OOS workshops were held, with breakout group reports providing new insights and recommendations. In 2002 the company Orbital Recovery promoting life-extension services to GEO ComSats was formed and evolved into a European industry-led consortium, later known under several different names called SMART-OLEV focused on life extension services via a space tug solution. This project has also been retired later. Furthermore, last decade several other

OOS-related projects and missions became prominent, i.e. NASA-DART, Orbital Express, DARPA Phoenix or HERMES-GEORing, to name just a few. After the TECSAS mission did not become a reality, a few years later a German mission named DEOS was prepared, however, got cancelled earlier this decade [3,4,5,6].

It was also discovered in collaboration with space insurance that OOS could benefit spacecraft reliability in the long-term [2] assuming timely exchange of spacecraft subsystems.

DLR's interest in OOS remained strong however, as it did in other countries, primarily in the US. Over the years it was recognized that OOS may deserve a distinction in terms of systemic definitions and to separate robotic-based servicing manipulation from enabling system design to make servicing a reality. Since 2010, the German space program addresses two programmatic lines in the context of OOS. Taking into consideration that - besides i.e. life extension, re-orbiting or re-fueling - any future OOS will require cooperative targets, hence space infrastructure elements designed to be serviced, DLR nowadays distinguishes between "active" and "passive" OOS. Active OOS comprises robotic technologies and capabilities to conduct any of the various "services" discussed, investigated and promoted by the global space community. Whereas passive OOS is geared around the necessary components enabling OOS. In other words, the latter means standardized functional building blocks and interfaces as pre-requisite for OOS. A Prominent activity is iBOSS - intelligent building blocks for on-orbit satellite servicing and assembly - the theme of this paper. iBOSS is a collaborative research program funded by DLR Space Administration. The project is being conducted by the iBOSS consortium comprising the renown German institutions TU Berlin (system lead), MMI and SLA of RWTH Aachen University, FZI, RIF and JKIC.

Nowadays multiple actors are actively the addressing OOS and OOA, with some even going as far as OOM. While ATK with ViviSat was the first 2nd generation player promoting life extension, currently several both government and private sector activities give a new boost to OOS. Examples are SSL, Effective Space Solutions, Astroscale, Space Infrastructure Services, Airbus Defense and Space, and so on.

iBOSS originates from the idea of modularity, effectively developing new standards facilitating and paving the way for OOS. Standardized functional building blocks and connecting standardized interfaces represent the core of this approach. Hence, new standards and opportunities for the industry.

The iBOSS has evolved to an end-to-end approach to OOS, with a technical core objective geared around a building set, hence a catalogue of standardized functional building blocks, connected by a standard interface supported and enabled by sophisticated software tools for both developers and customers. Concomitant economic assessments delivered interesting results as e.g. substantial cost saving in AIT, as well as increased mission flexibility or deferred design decisions, hence, tangible commercial value.

3. iBOSS Approach: Technology in Brief

Today satellite systems have no OOS capability. The failure of a vital component or subsystem leads to a reduced mission performance or to a complete mission loss. In such cases the damaged satellite systems often must be deorbited or put into a graveyard orbit. In this process, all still working and valuable components, subsystems or scientific instruments are lost too.

Challenged by this problem a full modular satellite architecture with OOS capability was developed within the iBOSS project. The main concept subdivides the common satellite bus on component level and integrates these components or even full subsystems in standardized cubic shaped building blocks, called iBLOCKs.

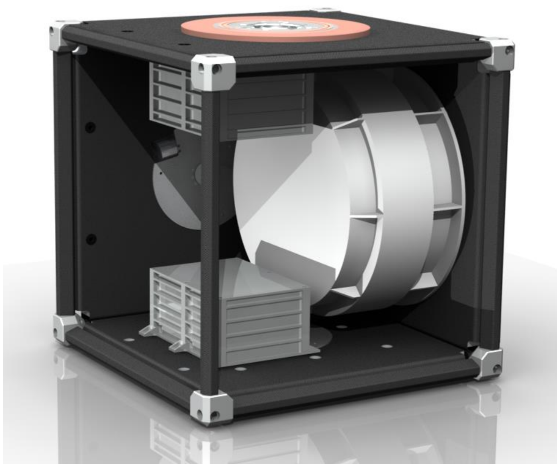

Fig. 1. Components Integrated into iBLOCK

This leads to a building block catalogue, compare Fig. 2, which provides standardized blocks, like a reaction wheel or battery block. The iBOSS vision aims at introducing new standards to arrive at some sort of LEGO in space, or PnP in industry terms.

In a following assembly step, the iBLOCKs are linked together using multifunctional interfaces iSSIs. This interfaces not only connect the blocks or modules mechanically, but also transfer electric and thermal energy and establish a data link between the iBLOCKs.

Fig. 2: iBOSS Catalogue Systematics

Hence, the full satellite bus is reassembled in a modular way and ready to be launched into space. Conducted studies show that a common satellite bus like ADM-Aeolus can be replaced using about 20 iBLOCKs [11].

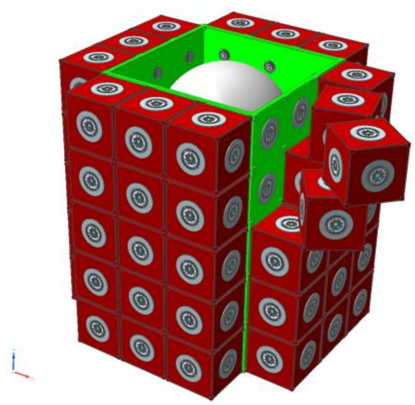

Fig. 3. Satellite Bus Made of Load-Carrying Central Structure (green) + iBLOCKs (red)

The OOS capability is given by the iSSI ability to couple and decouple the iBLOCKs in orbit. This allows e.g. a robotic servicer satellite to remove or add modules to a satellite system in situ. Damaged or outdated components and subsystems can be replaced, the satellite system can be upgraded by adding new modules to the system. In case of a satellite's end of mission the full modular architecture can be taken apart and its modules are reused as spare parts for other iBOSS like satellites or to assemble a complete new satellite in space. The servicer stays in orbit, receives new iBLOCK supplies from earth and services fuel efficiently a fleet of iBOSS satellites in his domain.

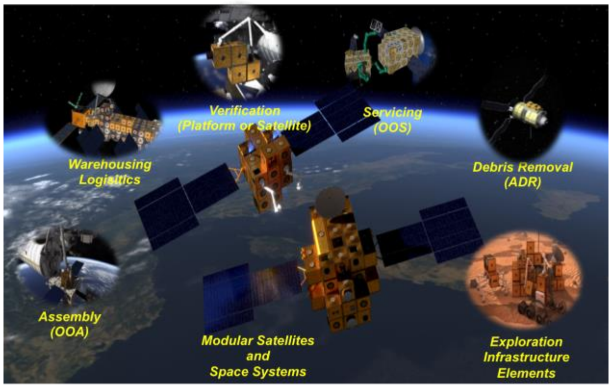

Fig. 4: iBOSS Building Set for Numerous Space Applications

3.1 iBLOCK – Intelligent Functional Building Block

The iBLOCKs or system blocks holding all required satellite bus components are not part of the main load carrying structure. As shown in Fig. 3 the iBLOCKs are connected to central structure which supports all launch loads and introduces them into the launch adapter. The central structure can hold also additional propellant tanks and an apogee motor, depending on the mission requirements. The iBLOCKs must support only their own weight and are connected with releasable launch locks, e.g. Frangibolts, to the central structure. Every iBLOCK hosts 3 to 6 iSSI, which are connected to the central structure and to neighbouring blocks. Once in space the launch locks are released and the iSSI takes over the mechanical connection, which in space has far lower stiffness requirements than during launch. This approach of function separation allows to reduce the iBLOCKs and iSSIs structural mass and therefore allows the cost-efficient manipulation and transport of the iBLOCKs in orbit.

The iBLOCKs are cubic shaped with a side length of 400 millimetres offering enough integration space for most common satellite components. Larger components like a propulsion system can be integrated into modules of multiple size.

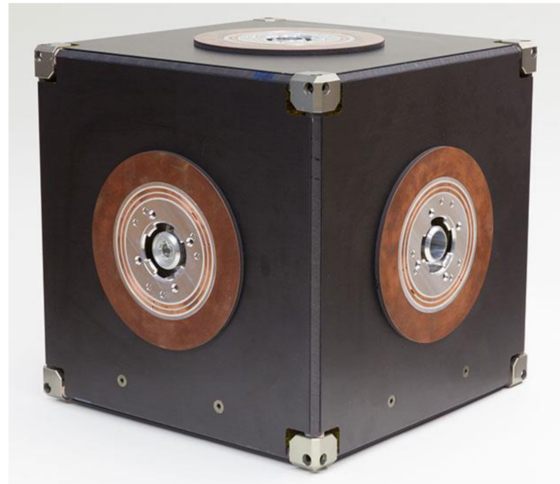

Fig. 5: iBLOCK Frame Panel Structure (with integrated iSSIs)

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The favoured design for the iBLOCKs is a frame structure, consisting of 12 CFRP beams with are adhesively bonded to 8 aluminium corner nodes. The frame is stiffened by CFRP sandwich panels which are bonded to the beams. The cover panels necessary to integrate the components are bolted to the corner nodes. Components and subsystems are mounted to distinct sandwich panels which provide a standardized insert pattern.

Every iBLOCK hosts with every iSSI also an ICU and ODBH which controls all vital functions of the system. The iBLOCKs are linked to each other building up an intelligent computer network which controls all functions of the satellite system. Power and date can be rerouted through the satellite if an iBLOCK fails. Computing capacity can be compensated by the network and offers a high system redundancy.

3.2 iSSI – intelligent Space System Interface

The iSSI is the main element of the system which is used to interconnect the modules and enables on-orbit servicing in the envisioned way.

To create a fully functional system the interface needs to be capable of transferring mechanical loads to guarantee the structural integrity of the satellite and the transfer of an electrical current needs to be implemented to power the modules. Furthermore, data needs to be exchanged to command the modules and as the fourth component also the transfer of heat is required to enable a feasible thermal control setup. In order to combine these four components a complex mechanism is required which needs to comply with further requirements to create a fully robotically serviceable system.

These requirements lead to the development of a completely new concept for these kind of coupling interfaces as a suitable mechanism could not be found in any other current concept for a modular satellite.

For the design two main topics for the definition of requirements were considered. First, the mission specific requirements which are mandatory for all space missions, such as the resistance to space environment, static and dynamic loads and a high level of redundancy. The level of redundancy plays an even more important role in this design due to the on-orbit servicing scenario.

The second group of requirements is based on the desired level of modularity. The cubic shape of the building blocks allows for a high flexibility when arranging the modules. To utilize this theoretical flexibility the interface layout needs to be designed accordingly. It was deemed most important to feature an androgynous design of the interface which eliminates having to follow a predominant direction. Furthermore, the interface needs to be rotatable in 90° steps to comply with the cubic geometry of the modules. Also, to ease the robotic manipulation of modules in larger assemblies the interface shall be fully retractable.

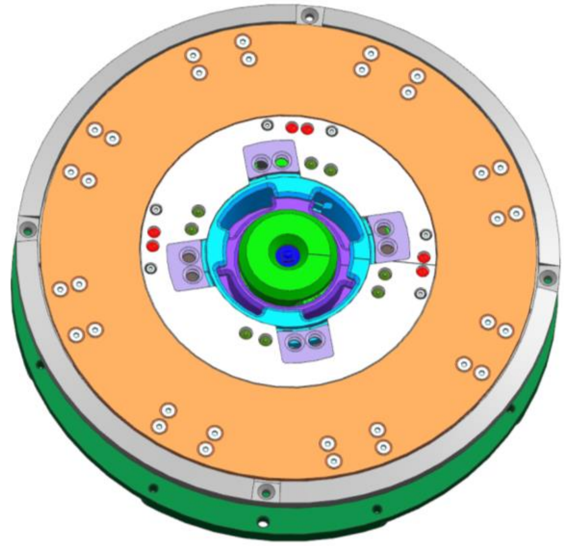

Fig. 6: iSSI Model (third version) with all four sub-assemblies [8]

Fig. 6 shows the current development status of the interface with the four subassemblies for power, data, heat and mechanical load transfer. In the centre of the mechanism the optical system for the data transfer is located. Around this are the main parts of the mechanical interface are positioned. Close to this the pins and corresponding sockets used for the electrical connection are mounted. The thermal interface which utilizes a special carbo-nanotube copper-alloy composite occupies the outside of the mechanism.

A main advantage of the androgynous design is the increased redundancy as both interfaces of the connection can initiate the coupling process. Furthermore, with this design it is possible to disengage the coupling with passive coupling partner and provides the system with an even higher level of redundancy [8].

The interface has been continuously improved with regard to both functional capabilities and performance. Fig. shows the test setup for an early version of the mechanical interface for vibration testing. Multiple tests have been performed throughout

The development process on different versions of breadboard models to test and evaluate changes and improvements. Fig. 8 shows the second-generation breadboard model of the mechanism with the integrated electrical interface. However, this concept did not comply with the set performance requirements for the electrical connection and was thus changed to the more capable pin-based design in the current version.

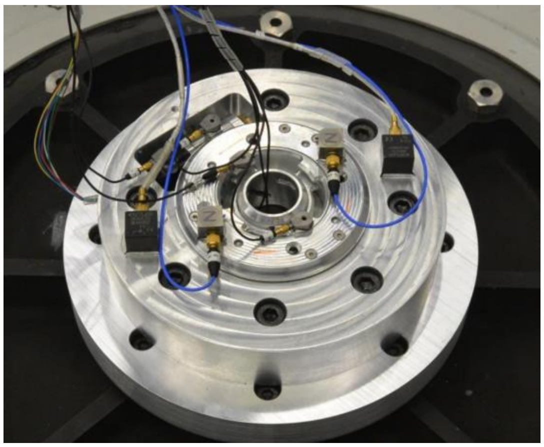

Fig. 7: first development breadboard version of the mechanical parts of the interface mounted on a shaker for vibration testing [8]

The mechanism is also equipped with different sensors to detect for example the operating temperature or the position of the mechanism. Operation of the interface is controlled and commanded by a dedicated controller hard-and software which is fitted to every mechanism. For the design of the mechanism an international patent has been issued. [10]

3.4. VTi – Virtual Testbed iBOSS + iCASD – intelligent Computer-Aided Design

In order to handle the technical complexity and to bridge the gap between technical and economical requirements and impact, iBOSS scenarios are modelled in a comprehensive virtual test bed (VTi). With combined virtual reality and 3D simulation techniques, both the potential and limits of modular systems and options for their robotic manipulation in space can be explored and demonstrated. This supports communication with decision makers in government and industry organizations by integrating technical with economic arguments.

Fig. 8: Second generation breadboard model with integrated electrical interface [7]

The VTi combines simulation models for the relevant physics aspects (orbital mechanics, multibody dynamics, solar energy input, …) with simulation models of the satellite components themselves (building blocks, mechanical interfaces, sensors and actuators, …) and control algorithms (robot control, attitude control, …). To provide reliable predictions, all simulation models must be verified, validated, calibrated and adjusted. To this end, reference experiments are conducted in a physical testbed and in the virtual testbed. From these laboratory scenarios, we can then extrapolate to application scenarios.

In the following, we describe how a future life cycle of a communication satellite based on the iBOSS design may look like and how the VTi supports the development of satellite design and servicing strategies.

Based on the requirements of the customer, a modular satellite is automatically generated with the iCASD Tool. The iCASD chooses building blocks and components from a standardized and extensible catalogue and describes the satellite using an XML-based modelling language. Before going into production, this satellite model has to pass a virtual system test. Fig. 9 shows an example of a modular satellite in the VTi. The satellite is propagated on its orbit according to SGP4/SDP4. In the particular test in Fig I, thermal and energy budget of the satellite is analysed. After passing the virtual system test, the satellite can be assembled and launched*. After maybe 10 years of operation, the customer needs to extend his satellite, potentially with a new set of transponders. From current and target configuration of the satellite, a reconfiguration plan can be generated and executed in the VTi After verification of the overall rendezvous and docking and robotic manipulation process in the VTi, it can be applied to the real satellite.

In all phases of the life cycle, the VTi can be used for decision support and optimization. For example, satellite and robot trajectories or their combination can be optimized for minimal energy consumption. Different options can be analysed and compared concerning their overall risks and costs (e.g. interrupting the client's satellite operation for servicing versus servicing a satellite during operation resulting in higher risks and higher fuel consumption).

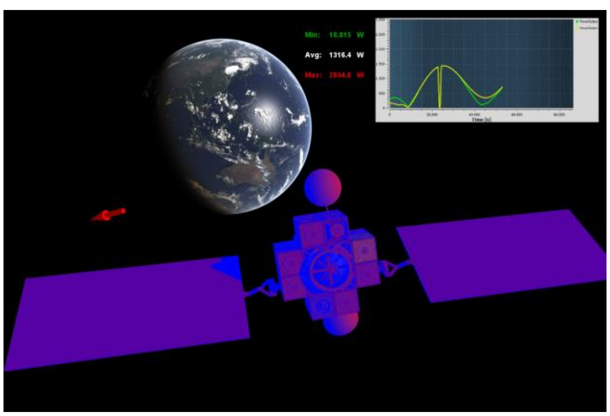

Fig. 9: VTi Test of a Modular Satellite

3.5 iSAT – iBOSS-based Satellites + Beyond

iSAT stands for an iBOSS-based satellite as explained above: fully modular or hybrids combining traditional satellite systems with iBOSS-elements. The following image gives an impression if iSATs in future operations.

Fig. 10: iSAT in Operation (Impressions)

3.6. Technology Roadmap and Way Forward

Current plans foresee ground qualification of key iBOSS technology features, the iSSI and iBLOCK to be finalized by mid 2018. In a next step, multiple options for staged IOD missions are in the process of assessment aiming at space qualification of iBOSS and subsequent introduction from 2020.

4. iBOSS Family Setup and Stakeholders

At first, iBOSS is a collaborative research program (since 2010) funded by DLR with means of BMWi. The project is being conducted by the iBOSS consortium mentioned above with TU Berlin as system lead.

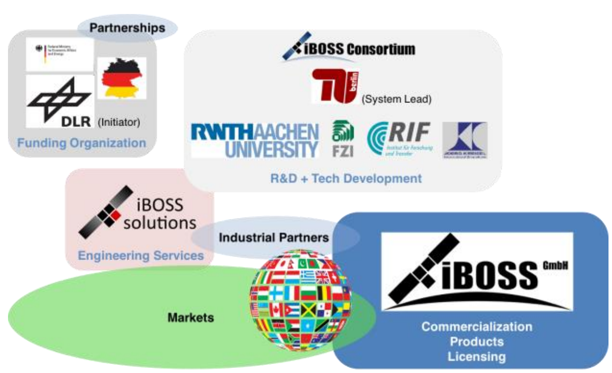

Fig. 11. iBOSS Family

As iBOSS has gained international attention and its technologies have matured to TRL 6, timely commercialization of iBOSS is envisaged in a phased approach. For this purpose, a dedicated commercialization entity, the iBOSS GmbH has been set up to market iBOSS products and services to the international community by sale or licensing depending their application and commercial feasibility, as well as to enter into industrial partnerships. A second company, the iBOSS Solutions GmbH provides associated engineering services and bundles iBOSS know-how and personnel for the longer-term. Since OOS and iBOSS capabilities are or international relevance and provide multiple options for international partnerships at governmental level, DLR remains a strong supporter aiming at fruitful projects

5. iBOSS GmbH for Commercialization

The iBOSS GmbH - as introduced above - acts as a catalyst between the iBOSS Consortium and the "market". Since modularity in space, especially spacecraft cellularization are yet in the making (also by other parties addressing similar topics), an early interaction with potential users is essential and of mutual benefit. Therefore, the iBOSS commercial offering is to provide "Standards ENABLING YOUR Business" and to feedback user requests into the technology roadmap of the iBOSS family.

The following sections give a briefing on how iBOSS GmbH plans to serve the industry and agencies alike, to grass root appreciation of the iBOSS standards and to build future business partnerships.

5.1 Products and Services (generic)

Principally, all of the described iBOSS elements (iBLOCK, iSSI, FTI, iCASD, VTi and iSATs) represent commercial opportunities as they meet future market demand. From a market and business development perspective roadmaps and timelines need a distinct perspective.

In light of this, it can be anticipated - and is based of ongoing feedback with potential users and partners - that initial products will be of less ambitious and simpler nature, while full rollout of the entire iBOSS product range will develop in stages over time and based on successful introduction and application of first iBOSS products.

5.2 iBOSS Near-Term Market Prospects

To date, rather concrete requirements and specifications exist for the iSSI and the iBLOCK. While the iSSI has also a stand-alone product potential, initial simplified iBLOCKs can serve e.g. for hosted payloads or as universal, hence standardized, experiment box.

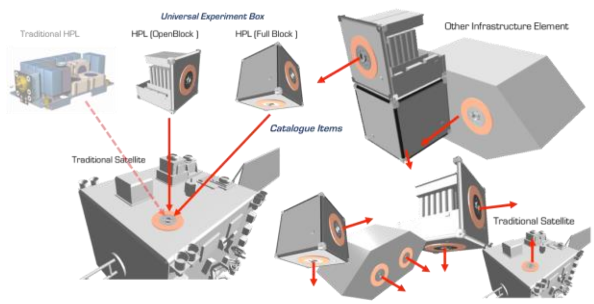

Fig. 12: iBOSS (Potential) Initial Products

The iSSI - as an (optionally) multi-functional 4-in-1 interface with fail-safe system capacity - combines mechanical, power, data and thermal connectivity. Applications basically range from any coupling tasks over extension features to any fashion of modularity element for PnP in space, comparable to USB in the IT world. The iSSI comes therefore in the following combinable editions with the option to combine any with its mechanical core:

1) iSSI-M (mechanical)
2) iSSI-P (power)
3) iSSI-D (data), and
4) iSSI-T (thermal)

For initial iBLOCK editions, preliminary nomenclature comprises iBLOCK-HPL (for hosted payloads) and iBLOCK-X (for universal experiment boxes. Any of these can come in multiples of the basic cubic iBLOCK shape, e.g. 2x1 or 3x1 [12].

5.3 iBOSS Industrialization Model

Assuming sufficient levels of acceptance and implementation of iBOSS standards (iSSI and iBLOCKs) partly novel industrial realization is envisaged to best materialize on core competencies and value-add of different actors along the value chain.

Since - similar to automotive assembly, e.g. power train components – dedicated iBLOCKs (as e.g. battery blocks, or reaction wheel blocks) will integrated be pre-tested and qualified (AIT1), and integrated to entire iSATs (AIT2).

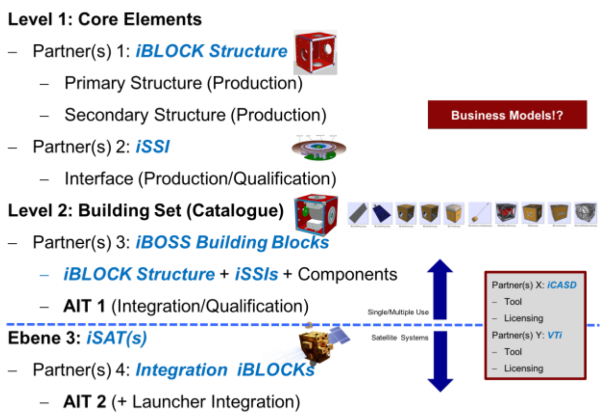

Fig.13: iBOSS Supply Chain (generic)

The IBOSS GmbH envisages iBOSS commercialization based on an industrialization model involving multiple partners ad different levels as shown above and offering licensing options and multiple business models along those lines. Current market demand and outlook, key technology TRLs and IOD timeline as well as pro-active propositions by potential industrial partners suggest a staged supply chain and iBLOCK catalogue management lending on the APP-store model and best following an open source approach. For the near-term, iBOSS GmbH will provide iSSIs and generic structural iBLOCKs for upgrade to intelligent functional building blocks by multiple value-added integrators (AIT 1) generating current and future (own) catalogue items (iBLOCKs) to complete and extend the iBOSS building set and its applications. Depending the various use cases, such iBLOCKs can either serve as self-standing solutions of can be integrated to hybrid or full iSATs by system integrators (AIT2).

With this philosophy iBOSS GmbH aims at providing “Standards ENABLING YOUR Business” in different business models ranging from straight sale (e.g. iSSI) to licensing (iBLOCK, iCASD, VTi, iSAT) or other synergetic collaboration to best serve the industry, help pave the way for OOS, OOA and OOM and to enhance the space eco system.

6. Conclusions

iBOSS addresses needs in the space sector and provides multiple solutions based on new standards enabling for OOS, OOA and OOM. Besides a sound basis of technological achievements and promising outlook on its technology roadmap and implementation, iBOSS furthermore can potentially generate other non-technical benefits [13]. The latter are cost reduction and economy of scale effects, higher mission flexibility and novel industry concepts. iBOSS thereby provides a straight forward solution for passive OOS, standardized modules supporting cooperative design principles ass a pre-requisite for end-to-end servicing.

Acknowledgements

We are grateful for the support by the other iBOSS consortium institutes and the German Aerospace Centre DLR Space Administration.

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