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INPPS Flagship with iBOSS Building Blocks

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Abstract

This presentation addresses iBOSS (intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly) as building blocks for non-nuclear sub-systems in INPPS (International Nuclear Power and Propulsion System) flagship. iBOSS are ideal mechanical, thermal, fluidic and data standardized building blocks to be used in autonomous robotic in-space assembly operations (referred to CAESAR (Compliant Assistance and Exploration SpAce Robot (CAESAR))) of INPPS in high Earth orbit above 800km. Additionally iBOSS will be used after non-human Mars return of INPPS, new replacements of INPPS sub-systems equipped in iBOSS for extended INPPS mission to Europa plus usage in a later first human Mars-INPPS mission. iBOSS building blocks are foreseen to be used in the non-human INPPS version (with wide wing radiators) in the second half of 2020th for space qualification - also already to Mars / Europa - and later in the 2030th in an arrow wing radiators version of INPPS flagship for human and cargo transport to Mars. These INPPS flagship versions with iBOSS were studied in a concurrent engineering study at DLR within the European-Russian DEMOCRITOS project. The study was supported by NASA Glenn Research Center and JAXA Tokyo. The result of the study related to iBOSS is, that the flagship will be - in considerable high quantity of the non-nuclear sub-systems - be equipped with iBOSS and iBOSS interfaces. For example, these sub-systems within iBOSS are the tanks of the electric thrusters, the power processing units and the electric thrusters. The iBOSS interfaces are foreseen for the deployable boom, the payload basket as well as for the auxiliary solar power ring. Insofar these sub-systems contribute to advancements with respect to engineering, manufacturing, assembly, test verification, reliability and service to reach the ten years operation duration of the new advanced space system INPPS.

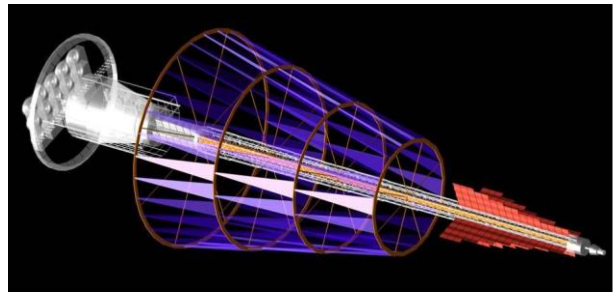
Keywords: 1) DEMOCRITOS & MEGAHIT Projects, 2) INPPS Flagship, 3) Human & Non-human High Power Space Transportation Hybrid Space Tug, 4) IBOSS building blocks for INPPS, 5) INPPS in-space assembly: CEASAR, 6) IBOSS for science, commercial and communication payload flights to Mars & Europa

Acronyms/Abbreviations

Artificial Intelligence (AI)
Attitude and Orbital Control System (AOCS)
Third US human space flight program (Apollo)
Compliant Assistance and Exploration SpAce Robot (CEASAR)
Demonstrators for Conversion, Reactor, Radiator And Thrusters for Electric Propulsion Systems (DEMOCRITOS)
Disruptive technologies for space Power and Propulsion (DiPOP)
Degree of Freedom (DOF)
Guidance, Navigation and Control (GNC)
intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly (iBOSS)
International Nuclear Power and Propulsion System (INPPS)
International Space Station (ISS)
Megawatt Highly Efficient Technologies for Space Power and Propulsion Systems for Long-duration Exploration Missions (MEGAHIT)
Moment of Inertia (MOI)
Nuclear Electric Propulsion (NEP)
Nuclear Thermal Propulsion (NTP)
Near Earth Space Environment (NESE)
Nuclear Power and Propulsion System (NPPS)
Nuclear Power Source (NPS)
Power and Processing Unit (PPU)
Power, Management and Distribution (PMD)
Strategic Research Cluster (SRC)
Telescopic Grid Structure (TGS)
Transport and Power Module (TPM)

1. Introduction

Building blocks with standardized mechanical, thermal, electrical, fluid and data are plus autonomous robotic assembly of structures in space is a key challenge to implement future missions like INPPS flagship (Fig. 1).



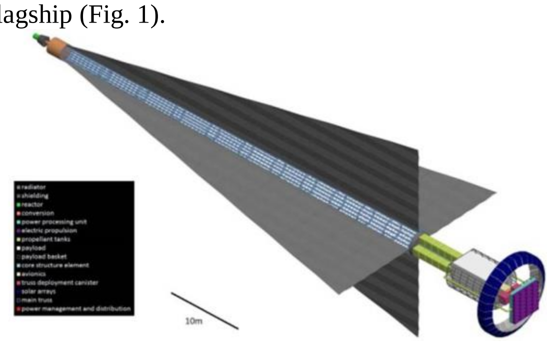


Fig. 1. Top - MARS-INPPS sub-systems with iBOSS building blocks. Bottom - first view of re-designed MARS-INPPS (for flight to Mars and Europa moon between 2025 – 2035) also contains about 15 – 20 iBOSS building blocks (see [1] to [6]).

The European Commission has set up the Space Robotics Technologies Strategic Research Cluster (SRC) in the Horizon 2020 program, with the goal of enabling major advances in strategic key points of this space robotic domain. To fulfil this objective, an European roadmap composed of three successive calls (2016, 2018 and 2020) has been defined by the PERASPERA consortium, composed by the main European space agencies. The first activities in the 2016 call have addressed the design, manufacturing and testing of reliable and high performance common robotic building blocks for operation in space environments. The specific objective of the second call in 2018 was to integrate these building blocks into ground-based demonstrators, towards applications of space robotics in the field of both orbital and planetary use. Therefore the PULSAR (Prototype of an Ultra Large Structure Assembly Robot) project was started as an operational grant no. 8. The reason: in case of future optical telescopes in space – greater than James Webb Space Telescope-, structures are too large to be self-deployed as a single piece [OG3]. A PULSAR mission would also use an Ariane 6 launcher.

Not only because INPPS sub-systems are also foreseen to be transport in higher Earth by the new European launcher, but also because the PERASPERA consortium and PULSAR project these many experiences are directly applicable INPPS flagship assembly.

Although the first humanoid robot is already in space operation, the general dexterity and sensing capabilities is automatically decomposed into a task sequence and then mapped to appropriate robotic skills. The autonomous execution of complex assembly tasks are not yet reached [8].

2. INPPS: Building Blocks and In-Space Assembly

Building blocks will have a great role for in-space assembly of large infrastructures in nearby future. In the next two subchapters this fact will be sketch for iBOSS related to the robotic in-space assembly for INPPS.

2.1. Aspects of iBOSS in INPPS

The MARS- and EUROPA-INPPS will be equipped with iBOSS common building blocks (15 – 20 blocks currently expected) for instance for the non-nuclear sub-systems, deployable boom, electric thruster tanks, PPU, core avionics, PMD and GNC. The payload basket, auxiliary solar power photovoltaic cells and the deployable boom will use iBOSS interfaces. AI for sub-systems within iBOSS levels up the human flagship preparation and flight safety of the entire flagship.

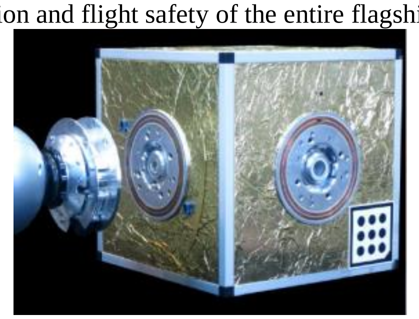


Fig. 2. INPPS autonomous robotic assembly will start in high Earth orbit with iBOSS sub-systems mounting of non-nuclear INPPS parts. First starts the rear end construction, continued via boom mounting – the last iBOSS equipped sub-systems - and finally ends with the physically non-critical core. This to be monitored procedure displays directly the successful realization of the launch and assembly for the flagship. This order of assembly using iBOSS – including AI – sustains the safety of a significant space project with a public 'visibility' potentially comparable to Apollo or the ISS.

iBOSS, funded by DLR and developed in Germany contributes something very important: box shaped units will host the sub-systems with the very important feature – it have standardized mechanical, thermal, electrical and fluid interfaces. This is an immeasurable advantage for combining flagships designs, developments, tests, improvements (like AI systems for the sub-systems), replacements on ground, at high Earth orbit and interplanetary operations. Up-to-date usage of iBOSS: within the used iBOSS the sub-systems parameters can be directly monitored and elaborated for AI systems mounted within iBOSS. Thereby these AI systems are trained by empirical experiences – already during flagship's high Earth orbit flight and especially during long interplanetary flights. These trained AI systems realizes in real time potential sub-system faults and may learn to intervene. This raises considerably the (non-human / human robots) flagship safety. This tested combination of iBOSS with AI also levels up the human flagship preparation and flight safety.

An economic aspect is the new interplanetary economy, here via commercialisation of INPPS flagship payload capabilities (see also in [6]). iBOSS are building blocks, which may also be applied in and mounted to the INPPS payload basket. Different products – from simple processed goods to high-tech products – may be produced under very low gravitational force / microgravity conditions. These conditions changes during interplanetary cruise or during Earth or Mars departure and approach periods, which offers production for products under different microgravity levels. These manufactured 'Made in Interplanetary Space' items are released or transported back to Earth by small spacecraft (possibly down to cube-sat size). These new trademark items open completely new business cases. This is a logical step after present first space commercialisation enterprises such as the reusability of launchers. Interplanetary economy would work in parallel to the already well established orbital economy and potentially a developing lunar economy.

2.1. INPPS In-Space Assembly

The in-orbit assembly strategy for INPPS flagship is twofold: primary it is based on the autonomous, robotic assembly of all INPPS sub-systems in higher Earth orbit and secondary of transport of nearly all sub-systems by several, international launchers. The currently proposed primary in-orbit assembly strategy is based on different launches of INPPS sub-systems with governmental or private European, Russian, US, Japanese and other launchers. The launcher selection will be based on nearby negotiations between launching nations and INPPS sub-systems developers. The benefit of the primary in-orbit strategy is the involvement of many space faring nations with its attraction to their nations related to the high number of applications of in-orbit assembly procedures and launcher usages as well as launch risk reductions.

The strategy of in-space assembly with iBOSS is also considered in the DEMOCRITOS ground demonstration concept [9].

Because the strategy for in-orbit assembly and servicing has a profitable importance - for launchers, space robotics technology and services - contracts from European and international space organizations, for space and non-space industries will be awarded. Therefore an European / international 'High Power Space Transportation Program with Electric Propulsion' must be highly envisaged!

Depending on the financing volume of the 'High Power Space Transportation Program with Electric

Propulsion' the preferred, technical sub-systems contributions has to be discussed soon with international partners to focus - the re-designed flagship and the in-orbit autonomous assembly – on the space qualification and Mars/Europa missions between 2025 and 2035.

The order of in-orbit assembly is independent from the flagship mission: the work is focused on the idea to start with assembly of non-critical INPPS modules. All assembly procedures are based on results from successful ISS assembly, operation and knowledge. The assembly procedures is envisaged to include autonomous robotic study results (from European Commission funded SRC Robotics and European / national robotic heritages) to safeguard procedures for successful assembly of all non-critical modules in orbit. It is important to note that installation of non-critical modules will be carried out first. The flagship reactor will be launched finally from Russia by Angara rocket family.

Contemporary an in-orbit concurrent engineering study for the re-designed flagship is in preparation. Robotics assembly is a well-known and proven technology in various industrial fields e.g. car manufacturing and products for the consumer market. This knowledge combined with the gained experiences in setting up the ISS is sufficient to describe the robotics assembly strategy for INPPS.

The INPPS is a large space system consisting of several hundreds of components and sub-components. In analogy to the terrestrial case an assembly / servicing platform is needed. The assembly platform has to provide:

- sufficient space for storing components and semi-finished sub-components, faulty parts, …
- rendezvous and docking interfaces for automated cargo lifting-body spaceplanes
- power supply for the assembly robot systems, sensors, robot-tools, test and verification facilities.
- high bandwidth communication infrastructure to ground stations
- separate AOCS, as the dynamic impacts of working robots affect the pose of the platform and thus the communication systems.
- strategic distributed grapple fixtures for plugging the walking robots-
- and more.

The Pros to the platform are the high flexibility for the assembling. It yields greater independence on the sequence of component's deliveries. The setting up of the INPPS requires many spaceflights. E.g. in case of a production or transportation delay of one entity the negative influence to the others is not predictable. The space flights will be managed and ordered by different partners, different space agencies, performed by different launcher companies, and so on. Each member of the assembly process has its own priority list. Thus the assembly of the just available components is possible. In case of faulty components they are put aside for repair or exchange by new components. In the meanwhile the assembly of other components can go on.

With its own AOCS the platform is robust against the dynamic influences of the working robots attached to the platform. Only one AOCS system is needed for all moving systems on the platform.

The platform itself should be equipped with at least three dexterous robot arms 4m length each. With two 7-DOF robot arms the majority of the assembly tasks can be performed. Like the human the second robot arm is for holding and assistive tasks to the first one. Together with the third arm in analogy to the third hand all assembly tasks can be performed. Their kinematic design may be reduced. All robot arms will have an identical interface. This allows attaching the three arms to one crane like robot system of 12m length. The huge arm may be needed for the handling of larger sub-systems e.g. conversion, radiators or payload.

The robots get the power out of the grapple fixtures which are strategically distributed over the entire assembly platform. They enable the mobility for robots. Depending on the final, more detailed re-design of the INPPS it may be necessary to have also an independent space tug for dedicated servicing and assembly tasks. The INPPS space tug may also be equipped with one of the three robot arms. The robot arm will also be needed for inspection tasks during assembly.

The platform can also be used for testing and verification of assembled sub-components under space conditions. This may reduce the terrestrial simulation efforts.

The Cons to the platform is the additional effort for setting it up. You have to design an assembly factory, produce it, transfer it to space and operate it. But this kind of infrastructure can also be used for the second human INPPS deep space missions to Mars and servicing missions in LEO /GEO.

The deployable boom subsystem will be contained in a containment canister. While differing from the standardized iBOSS modules in size and shape, the deployment canister will hold one or several interfaces to the iBOSS system. Once assembled to the iBOSS power module and commanding structure, the boom deployment can begin.

Requirements and design drivers regarding the deployable boom subsystem requirements are the following aspects (not limited to): integrity, loads, stiffness, deployment and interfaces.

Hereby integrity is defined as the boom being in the state of being whole, or undiminished during the entire mission duration.

The loads will have to be defined in detail and were discussed in DEMOCRITOS deliverable [9].

The stiffness will result out of the requirements on payload and platform mass in conjunction with frequencies, tolerated by the attitude control system.

The deployment requirement is mainly a requirement towards autonomy, completeness and joint functionality of the boom deployment.

The interfaces are defined to match the standardized iBOSS system. Depending on size and shape one or more interface can be created. Those interfaces will also have to be capable of transferring power, heat and data (which is the case for iBOSS interfaces).

The currently existing deployable design is based around the assumption of a minimum needed deployed length of 23 m. Furthermore the flagship consists of two main segments: reactor/shielding/conversion and platform with tanks, payload, ETs etc. - which are connected via the boom. Each part will weigh approx. 10 metric tons leading to a first estimation of a boom specific mass of 100 kg / m.

For the primary structure a Telescopic Grid Structure (TGS) is proposed, one segment of this structure type was developed at DLR in Braunschweig. Grid structures are used for launcher inter-stages and payload adapter rings as they feature excellent strength and stiffness properties and are more lightweight than continuous shell cylinders. A telescopic mast composed of several nesting grid cylinders allows realization of large and lightweight primary structures for the heavy INPPS flagship. Components may be attached at both ends and in between as well by increasing the cylinder length. For deployment the longitudinal struts may be used also as guide rails for the enclosed cylinder, thus minimizing the need for additional components for deployment control. The free volume inside the stowed telescopic structure can be used for stowage of other sub-systems which increases the total packaging efficiency.

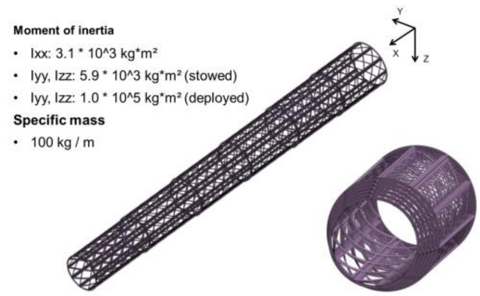


Fig. 3. Telescopic Grid Structure in deployed (left: 3 m diameter, 27 m length) and stowed (right: 3 m diameter, 4.5 m length) configuration.

The US PROMETHEUS project included a similar truss structure in the nuclear powered Jupiter spacecraft. The length was also about 20 m, similar to the boom length in INPPS flagship. This length is not only necessary for mounting the vast length of radiators. In addition this length also enables to reduce the density of flux of neutron and gamma radiation form the core sub-system extraordinarily. For INPPS flagship simulations (see in [2]) based on GEANT4 software - resulted into an about 10^{-4} lower neutron flux behind reactor core shielding. After the additional INPPS spacecraft shielding and behind the deployed boom distance (20 m), the payload basket and the other non-nuclear sub-systems of INPPS exposed by an extra 10^{-6} lower neutron flux (with 20MeV energy).

The presented grid structure is derived from existing DLR grid technology, which has been already developed in correlation with new launcher and adapter systems.

There are two possible options for the deployment of the boom. It can either be deployed empty, directly after being attached to the iBOSS system and supplied with power. Separately it could also be deployed after attaching the payload with its respective tubing and cabling. In the second case the loading during deployment will be a substantial design driver for the stiffness and robustness of the deployable boom. In either case, the boom can only deploy itself and potentially attached items in longitudinal direction (see x in Fig. 3). Secondary and tertiary deployment steps that might be necessary to span open an area (e.g. for radiators) will have to happen separately. Furthermore all items can only be attached to one ring per cylindrical element of the boom and only if the boom segments increase in length with decreasing diameter. During the in-space assembly no additional equipment are required for the deployment of the boom.

The boom power budget will depend on the loading during deployment (in the baseline design case) and once fully deployed and locked in place no additional power will be required. The boom mass budget is depending on the load case in static state (after deployment, for the fully assembled flagship).

Composite materials with low density and high stiffness are generally recommended for the boom truss. However areas with high thermal loads or high frequency loads need to have special attention. Hybrid composite-metallic laminates may also be used to improve thermal conductivity at some interfaces. These interfaces are the areas to the high-temperature subsystem like standard (high temperature) and droplet radiator (lower temperature).

INPPS non-robotic assembly may be an alternative approach setting up the INPPS by a small number of pieces can be implemented with classical space technologies. The production and assembly will happen on-ground. For example, three modules each having an own AOCS are transferred by three launches into higher Earth orbit. With this classical rendezvous and docking manoeuvres the INPPS can be assembled. This classical assembly approach can be compared with the assembly of ISS. The Pros of the classical assembly is the re-use of well-established techniques and systems. On the other hand with the new space initiative there starts a new thinking on the space technologies. E.g. the production and flying of 2000 satellites within a timeframe of few years is not possible with the traditional space production. A paradigm shift in space production will come in the near future. INPPS could benefit.

3. Conclusion and Outlook

The main conclusions of the paper are:

- building blocks like iBOSS will have a substantial influence for INPPS realization, safe flights and economic growth and
- autonomous robotic assembly of large space infrastructures – like INPPS flagship – will significantly contribute to optimal INPPS assembly in higher Earth orbit and servicing for several non-human and human INPPS missions.

The main outlook related to INPPS, building blocks and robotic assembly is

- integration of iBOSS and robotic assembly experiences from SRC into the ground concept realization of DEMOCRITOS INPPS,
- consideration of iBOSS in the final re-design of INPPS for 2025 – 2035 Mars and Europa missions,
- first robotic assembly study of the finally re-disgned flagship and
- preparation of international prospection of INPPS sub-systems mounting and robotic assembly.

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