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Recent Developments on DLR`s Post-ISS Concept

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Abstract

What will happen after the International Space Station's operational lifetime ends? How could a future crewed Low Earth Orbit (LEO) platform look like with the lessons learnt from the ISS experience in mind? How could a future role share be organized and what use cases and applications could a future platform offer? What is the long-term big picture for future human LEO activities? These questions are currently under investigation in the course of the German Aerospace Center (DLR) "Post-ISS" activities.

A very promising answer is proposed by the Orbital Hub concept which has been developed by DLR's System Analysis Space Segment department in Bremen together with scientists, international space industry and recently together with international institutions using DLR's Concurrent Engineering Facility. The concept consists of a small modular crewed part called Base Platform and a dockable, serviceable, but uncrewed experiment platform referred to as Free Flyer. One major advantage of such a scenario is the decoupling of the habitat and the payload platform leading to higher flexibility, reduced attitude and pointing restrictions as well as less security concerns.

The single modules of the Orbital Hub have been designed under the premise of modularity and each with their own dedicated functionalities and responsibilities. Therefore, they could also be used as building blocks for different platform concepts together with modules from other international partners and re-used ISS parts to serve for diverse mission objectives and political requirements. In the long-term, the DLR vision is to have the Orbital Hub as a central node of a platform cluster building up an environment for resource sharing, exchange and collaboration in LEO, referred to as "Space City".

The present paper gives an overview about the technical design, development progress and ongoing activities around this concept including e.g. joint studies with international partners. The paper assesses the possible combinations of the Orbital Hub modules together with both existing ISS parts and spacecraft under development or planned for the future. Furthermore, it offers an outlook on the role and opportunities of the Orbital Hub or similar platforms in the context of larger LEO formations for human space-flight.
Keywords: Post-ISS, Orbital Hub, Free Flyer, Space City, Human spaceflight, International Space Station

Acronyms/Abbreviations

AIT	Assembly, Integration and Test
APAS	Androgynous Peripheral Assembly System
CBM	Common Berthing Mechanism
CER	Cost Estimation Relationship
CST	Crew Space Transportation
DLR	German Aerospace Center
ECLSS	Environmental Control & Life Support System
HTV	H-2 Transfer Vehicle
IBDM	International Berthing Docking Mechanism
IDA	International Docking Adapter
IDSS	International Docking System Standard
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JEM	Japanese Experiment Module
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
NEM	Science and Power Module
PMA	Pressurized Mating Adapter
TRL	Technology Readiness Level

1. Introduction

The International Space Station (ISS) is clearly the greatest endeavour and achievement for human spaceflight in Low Earth Orbit (LEO), not only because of its great success and manifold scientific results over the almost 20 years of operation but also due to the cooperation of the 15 international partners. The ISS still receives support by all partners and its operation has been ensured until at least 2024. Moreover, this date is still not seen as the ultimate lifetime of the ISS and could be extended if sufficient funding is available. Nevertheless, at one point the ISS will inevitable have to be retired leaving a big vacuum for all current and potential future LEO user and applications.

Looking at the recent exploration plans and roadmaps of space agencies and authorities, it becomes clear that LEO spaceflight shall be overcome to open up for greater goals like crewed Mars exploration, Moon bases or deep space habitats. Human spaceflight in LEO shall, if at all, be conducted by purely commercial platforms. [1] These exploration plans are on the one hand very visionary but on the other hand also very ambitious as they require a lot of technologies to be developed (e.g. capable launchers and life-support systems) and have to be considered as hardly feasible with current financial budgets. DLR`s Post-ISS project, initiated already in 2013, aims at the intermediate step and is specifically looking at feasible and payable platforms to ensure continuation of LEO human spaceflight. The associated systems studies comprised of an assessment of lessons learned from ISS operations, analysis of actual user requirements and potential applications, concept selection and detailed technical design of the most promising solution. The result of all these activities is a small but extendible platform referred to as Orbital Hub, consisting of a crewed base and a free-flying element.

2. Technical overview: Orbital Hub

The concept of DLR´s Orbital Hub has been described in detail in [2]. This chapter aims to give a brief descriptive overview on the main modules and their functionalities in the overall scenario. Additionally, the progress which has been achieved in defining the operational scenario and cost estimations will be addressed.

2.1 Architecture

Both parts of the Orbital Hub, the Base Platform (Fig. 1) and the Free Flyer (Fig. 2), consist of functional elements and modules, each with a dedicated purpose, which shall be explained in the following and are presented in Fig. 3.

2.1.1 Base Platform

The Base Platform consists of three main modules: the docking node, the service module and the expendable habitat. The docking node is the approach point for any crew-/ cargo visiting vehicle with four available docking ports. Additionally it accommodates a cupola, crew training equipment and subsystems for communication, data storage and contingency propulsion.

Attached to the docking node is the service module, as the central part of the Base Platform. It houses the basic bus functionalities (mainly power supply, thermal control), a toilet and the externally mounted Control Momentum Gyros (CMGs) for platform orientation.

Fig. 1. Cross section of the Orbital Hub`s crewed Base Platform (Artists`s Impression)

The Expandable Habitat uses the BA330 by Bigelow Aerospace as a baseline design. It ensures a comfortable living and working environment with sufficient space for the crew. It contains three crew quarters, food provision, storage, workstations, manufacturing and laboratory racks for human physiology. A small airlock is included for contingency cases when EVAs are inevitable.

2.1.2 Free Flyer

The Free Flyer has three functional elements: the pressurized laboratory, the external platform and the service module. The pressurized laboratory is the only area of the Free Flyer which is accessible by the crew and additionally only in docked state to the Base Platform. It provides sufficient volume for payload which needs to be pressurized, e.g. material sciences, crew workstation for experiment preparation plus maintenance and an airlock to equip the attached External Platform. The External Platform is a truss element with standardized payload interfaces providing mechanical connection, power and data supply as well as thermal conditioning. The External Platform is serviced by robotic means using a mobile robotic manipulator.

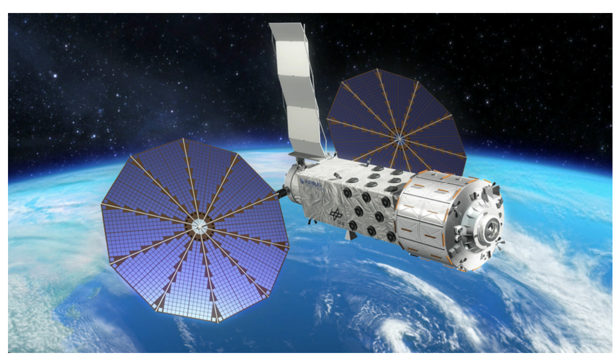

Fig. 2: Orbital Hub`s Free Flyer in an unequipped state (Artist`s Impression)

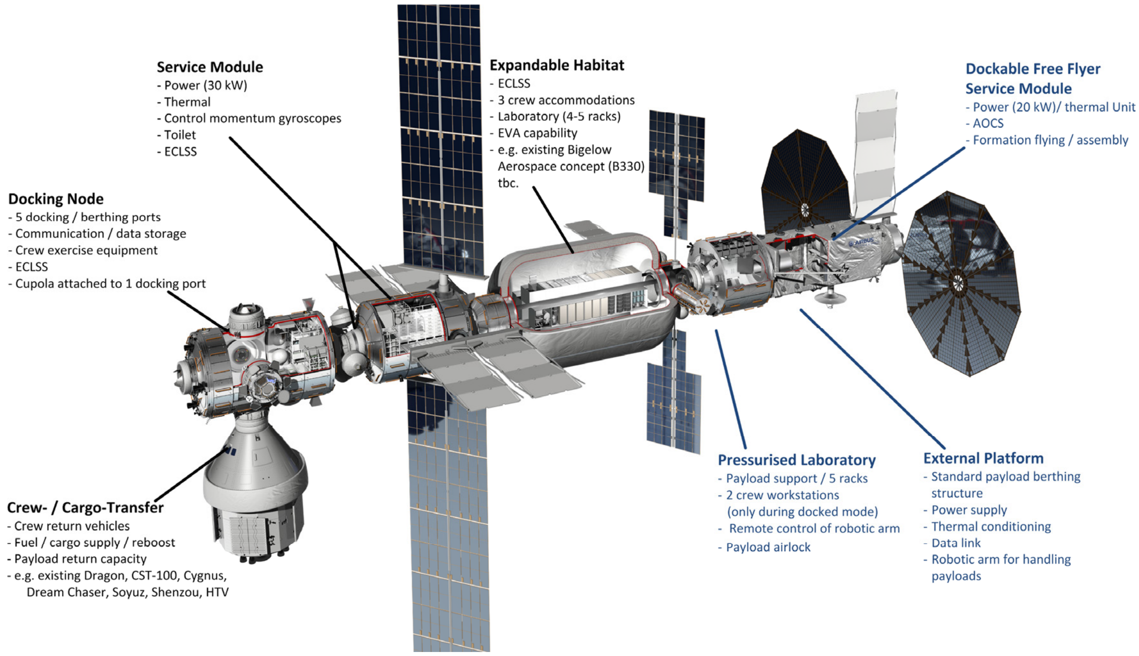

Fig. 3. Modular Orbital Hub architecture comprised of a multi-purpose platform with dockable free-flying module.

The service module section is a direct extension of the truss structure and, similar to the Base Platform counterpart, accommodates mainly power, thermal, propulsion and data handling systems.

The Free Flyer is the active part of the Orbital Hub scenario during assembly phase and rendezvous and docking, requiring impulsive thrust. Furthermore, during the free-flying campaigns the payloads demand an undisturbed environment and high quality microgravity, which leads to the necessity of continuous thrust. For this reason, the Free Flyer is equipped with a hybrid propulsion system with both chemical and electrical thrusters to meet the different thrust requirements of the multiple applications.

2.2 Assembly Phase

The Free Flyer is the first object in orbit with the potential to cooperate with the still existing and operating ISS during its first missions. Its mass and stowed volume has been optimized to be launched with a single Ariane 6. For the setup of the Base Platform, the Free Flyer is the active part during assembly of the single modules. The first module of the Base Platform to be launched is the Expandable Habitat by a heavy launcher such as Delta IV, Proton or Falcon Heavy. The Free Flyer docks autonomously to the Habitat and waits for the next module, which is the Service Module. The platform is completed by the Docking Node. The Free Flyer collects the modules subsequently. Only after all these steps have been completed successfully and the functionality of the Base Platform can be ensured, the first crew arrives with any compatible crew vehicle (e.g. Dragon V2, CST-100 Starliner, Soyuz, Dream Chaser (Crew) or Shenzhou).

2.3 Flight Plan

The complex interaction of two decoupled spacecraft with different propulsion technologies in formation flight like the Free Flyer and Base Platform has to be analysed carefully. Especially the timing and role share between Free Flyer, Base Platform and visiting vehicles for manoeuvres during rendezvous and docking, orbit raising and debris avoidance in combination with the required flight direction of the Base Platform needs to be taken into account. Further aspects are refuelling and maintenance of the Free Flyer, docking interface occupation as well as cargo and crew supply visiting vehicles. Considering all these aspects, an exemplary flight plan for one year of operation has been created leading to two Free Flyer campaigns in average with a duration of approx. three month each.

2.4 Cost estimation

A lot of work has been conducted to refine the model for cost estimation of the development and operation of the Orbital Hub. The development costs have been assessed using a bottom-up approach on component level using mass-related Cost Estimation Relationships (CER) derived from experience. The detailed model includes cost for hardware incorporating Technology Readiness Level (TRL) and test philosophy of components, personnel, management, Assembly, Integration and Testing (AIT) and miscellaneous other wrapping costs.

These costs are completed with operational cost for launches during assembly, crew / cargo supply and mission operations for 10 years based on DLR experience and available data.

The results are a total cost for development, set-up and operation over 10 years for the Free Flyer of 3.0 B€ and 12.5 B€ for the Base Platform. This leads to an estimation of an overall average cost of 1.5 B€ per year. The Free Flyer could be realised for an average cost of 300 Million € per year and can be seen as a realistic low cost solution for a first flying hardware of the Post ISS scenario.

3. Building blocks for future LEO platforms

After definition of the scenario in all technical detail, the main task currently is to synchronize the results with Post-ISS concepts of international partners from governments or industry for potential collaborations and common strategies. This would facilitate and support the implementation by sharing the cost and contributions for such a small LEO platform. To enable this, it is important to be as modular as possible and as flexible as necessary to find the most suitable solution also under the aspect of international policies. This chapter assesses the modular approach of the Orbital Hub and the type of activities enabled by this design approach. A first compatibility analysis of Orbital Hub modules as building blocks of future platforms with other current modules is shown.

3.1 Modularity

One requirement and prerequisite during the design process of the Orbital Hub scenario was to be as modular as possible under technical and political aspects.

Technical modularity in this context stands for the possibility to use single modules in different combinations by usage of common interfaces and to allow for an exchange or replacement of single modules in case of failure or malfunction.

The first step to facilitate technical modularity was to require the usage of standardized interfaces between the modules. The selected International Berthing and Docking Mechanism (IBDM) is the European implementation of the International Docking System Standard (IDSS) and through this is compatible with future supply vehicles or additional modules following this standard (as e.g. NASA`s International Docking Adapter, IDA). The IBDM adapters are consequently included as interfaces between the single modules of the Orbital Hub Base Platform and the Free Flyer as well as for all ports at the Docking Node. This provides freedom for the selection of crew-/ supply-vehicles, for possible platform module combinations and configurations.

Each of the single modules of the Orbital Hub (as shown in Fig. 3) has its dedicated purpose and functionality (i.e. habitation, service module, docking port and payload platform). This brings the advantage that modules could be exchanged / replaced during the early design stages without severe impact on other modules and the overall design. Additionally, the benefit of the decoupled Free Flyer as primary payload platform has the big selling point that the selection of the payloads does not have a direct impact on the Base Platform, as the Free Flyer can be seen as an independent system with own resources. It has been designed by the help of a wide range of strawman payloads to provide sufficient capabilities for future applications of any type. Even if the Free Flyer as it is currently foreseen has to be updated, redesigned or replaced by other systems with the same basic capabilities, it can be done dissociated from the Base Platform itself.

Political modularity has been required to be open for contributions of different partners according to their individual financial budgets, expertise and scientific, commercial and programmatic interest. This means that the concept allows for international cooperation on different levels and aspects, also supported by the technical modularity explained above. Example contributions could range from single payloads or sub-systems, via crew provision or supply missions to complete modules. The obvious benefit is a share of development and operational cost but also utilisation of specific knowledge and expertise shall not be underestimated. On the other hand, lessons learned from ISS show that a big consortium of partners lead to excessive overhead and reduced the agility for decision making and operation. The platform should be realized with as much partners as necessary to be feasible but as few as possible to counteract against the slow and costly operation of a huge platform as ISS. The Free Flyer especially has been designed to be compatible with the current ISS and could be realized as first flying hardware of the Orbital Hub within the ISS´s remaining operational lifetime. This would guarantee a smooth transition and could pave the way for future applications and additional funding.

3.2 Compatibility analysis

Based on the current Orbital Hub concept and enabled by its modular approach described above, possible combinations with modules from international partners have been analysed to define possible alternative platform concepts. Thereby the Orbital Hub modules were used as building blocks for the new architecture together with both existing modules (i.e. re-used from the ISS) and spacecraft which are currently under development. It has been found that any platform should consist of at least four main functional parts:

servicing, habitation, docking and payload. These functional parts are not limited to be single modules but could consist of several to be in line with launch limitations or recent developments (e.g. two small modules are launched and combined in orbit to function together as service module).

Table 1: Compatibility matrix of Orbital Hub modules with existing ISS modules currently in orbit, existing and planned visiting vehicles and planned future modules.

		Orbital Hub			
	Module combination	Docking Node	Service Module	Habitat	Free Flyer
ISS (in Orbit)	Zarya	Age > 15 years			
	Zvezda	Age > 15 years			
	Pirs	Age > 15 years			
	Piosk		(x)	(x)	(x)
	Rassvet	(x)	(x)	(x)	
	Unity	Age > 15 years			
	Destiny	Age > 15 years			
	Harmony		(x)	(x)	(x)
	Tranquillity		(x)	(x)	(x)
	Cupola	(x)			
	Leonardo	(x)	(x)		(x)
	Kibo	(x)	(x)	(x)	(x)
	Columbus	(x)	(x)	(x)	(x)
Visiting vehicles	Soyuz	(x)	(x)	(x)	(x)
	Progress	(x)	(x)	(x)	
	HTV	Berthing required			
	Dragon V1	Berthing required			
	Cygnus	Berthing required			
	Shenzhou	(x)	(x)	(x)	(x)
	Dream Chaser	x	x	x	
	CST-100 Starliner	x	x	x	x
	Dragon V2	x	x	x	x
Future modules	Nauka				(x)
	NEM				(x)
	Oka-T	(x)	(x)	(x)	
	Bigelow	x	x		x
	Axiom	x	x	x	x
	Bartolomeo			Applications	

(x) Docking adapter required

Table 1 is a product of a preliminary analysis of theoretically possible combinations of the Orbital Hub modules described above with a) existing ISS modules currently in orbit, b) current and future visiting vehicles and c) planned future modules. For existing ISS elements, only the main pressurized crew modules are considered, omitting all truss segments, adapters and external platforms. This qualitative assessment looks at mechanical compatibility of docking interfaces, functional redundancy and compatibility as well as other limiting and easily accessible factors as e.g. lifetime issues of aged modules.

Greyed-out fields are combinations with redundant functionality (e.g. two modules with habitation functionality) or incompatibilities (e.g. Free Flyer with an uncrewed visiting vehicle) and are excluded from further analysis. Red fields indicate an incompatible combination, yellow stands for a theoretically feasible solution where adaptations are required (e.g. docking adapters for conversion of APAS/CBM to IDSS). Green fields specify a full supported, meaningful combination without additional adaptations. This leads to a wide range of theoretically possible combination which in a first step can only be analysed qualitatively. The main factors to find the suitable combinations within such a preliminary analysis should be:

a) Compatibility of modules
b) Completeness of required functionalities
c) Feasibility of assembly procedure in orbit
d) Performance in key factors of overall platform (e.g. crew size, power provision, payload capacity w.r.t user demand)
e) Role sharing
f) Cost estimation

By means of these main characteristics plus specific additional considerations and pros and cons, it is possible to quickly sort out any combinations which are technically unfeasible, under- / oversized or unlikely due to cost or programmatic reasons. An objective evaluation has to be conducted to rank the feasible solutions. Only the most promising solution is proposed for detailed investigations e.g. within a Concurrent Engineering (CE) study with direct involvement of technical experts from all participating partners. One example for such a successful collaboration was a joint study with JAXA in 2017, assessing more than 60 possible combinations of Orbital Hub modules, HTV successors (HTV-X) and the re-use of the Kibo laboratory. It condensed into one most promising concept, which has been studied in greater detail in a one week CE study.

4. Discussions

The compatibility matrix in Table 1 shall be discussed in more detail in this chapter. The ISS modules are designed with a nominal lifespan of 15 years. Now, due to the ensured extension of ISS operations until at least 2024, the oldest modules will reach an orbital lifetime of 26 years. Analysis show that the maintenance cost increase with the module`s age. [3] For this reason, it is unreasonable to re-use the oldest ISS modules for future LEO platforms, which in turn also are planned to have a lifetime of 15 years and more. A threshold has been introduced that all modules which by now already have exceeded their nominal lifetime (launch date before 2003) are considered as unrealistic for a combination with the Orbital Hub modules.

Modules which pass this first sorting step have to be analysed in more detail. Most of them have an outward position in the ISS configuration and thus theoretically could be re-located without multiple intermediate steps. The two American nodes (Harmony and Tranquillity) are exceptions. If they would have to be re-used, the adjoining modules would have to be re-located first or the complete complex would have to be transferred as one entity, if applicable (e.g. Harmony together with Columbus and JEM). In general it has to be stated, that it would have to be carefully analysed whether a re-use of existing modules with a reduced lifetime, which would have to be partly adapted, re-equipped and transferred would be beneficial compared to specifically tailored new modules which need to be build and launched.

As described in Chapter 3.1, the Orbital Hub decided to consequently implement the future-oriented IDSS both for docking of visiting vehicles and connection between the modules. For this reason, all potential partner modules equipped with older standards are not directly compatible. The IDSS incorporated heritage from the APAS and have the same passage diameter of 80 cm [4]. Thus, converters for these systems or design changes in future systems towards IDSS will be less complex than for the CBM. This would need an assembly which is both changing the diameter and allowing for automated docking. Such a conversion is already installed at the forward docking port of the Harmony node by a combination of a Pressurized Mating Adapter (PMA) and an IDA in the course of preparation of the upcoming commercial crew vehicles (CST-100 Starliner and Dragon V2).

Most of the currently operating cargo supply vehicles are relying on berthing with support of robotic manipulators. This intentionally has been excluded from the Base Platform design, as automated docking is assumed to be reliably mastered by all potential transport systems by the time the Orbital Hub would be available, facilitating the operation of the platform. For this reason the berthing transport systems (i.e. HTV, Dragon V1 and Cygnus) are incompatible in their current versions with the future Orbital Hub.

The external payload platform Bartolomeo proposed by AIRBUS to be attached to Columbus for commercial applications in its current version is very strictly optimized for the use in combination with the European laboratory [5] and thus, cannot easily be transferred to the Orbital Hub. Nevertheless, this platform is assumed to be a precursor and role model, additionally to the recent commercial use of the JEM External Facility [6], for the generation of demand among commercial users which directly could be transferred onto the Free Flyer as a next step.

5. Future visions

DLR`s longterm vision for future LEO activities is to establish a modular formation of collaborating structures and platforms. This concept uses the working title “Space City”, as it has similarities to characteristics of classical terrestrial cities. In contrast to the assembly process of the ISS where all modules are subsequently attached permanently to build up one growing platform, the Space City concept is more dynamic. Cities on earth can be hundreds of years old while they are consisting of single houses, which in fact are only a few years old. Continuous construction, modernization or exchange of the houses and infrastructure keep the city alive and operational, without the need to replace a complete city once the first components reach their ultimate lifetime. Single houses are owned and operated by different organizations using common infrastructure for e.g. transportation, commodities and resources. This simple concept should be followed also in the definition of future LEO architectures. Space City is exactly aiming at this by assuming a lose network of mini-platforms and spacecraft, sharing resources and fulfilling own or common tasks.

The Orbital Hub could be a first building, a nucleus, in this city with the functionality of a central element (hence the name “Hub”) for maintenance, preparation or modification of payload platforms (similar to the Free Flyer).This would have the advantage, that not all of the platforms need to be crewed permanently, but the organizations could share the operation of the Hub, while the small platforms would stay under their own responsibilities. Such a central logistics / distribution centre could be placed in an orbit which is suitable and easy to reach for the supply vehicles to transport the resupply items from ground into orbit. From there, the goods (e.g. propellant, consumables or payloads) could be transferred to the final recipient platform or picked up directly from there (c.f. freight transport / central warehouse). A similar concept is also imaginable for the distribution of astronauts onto smaller, only temporarily crewed platforms. The Orbital Hub could be seen as a basecamp, in which the astronauts are accommodated temporarily before and after their actual mission. Astronauts could visit several smaller platforms during a longterm mission and service them subsequently. The Orbital Hub is equipped with all necessary facilities for being permanently crewed (e.g. ECLSS, training

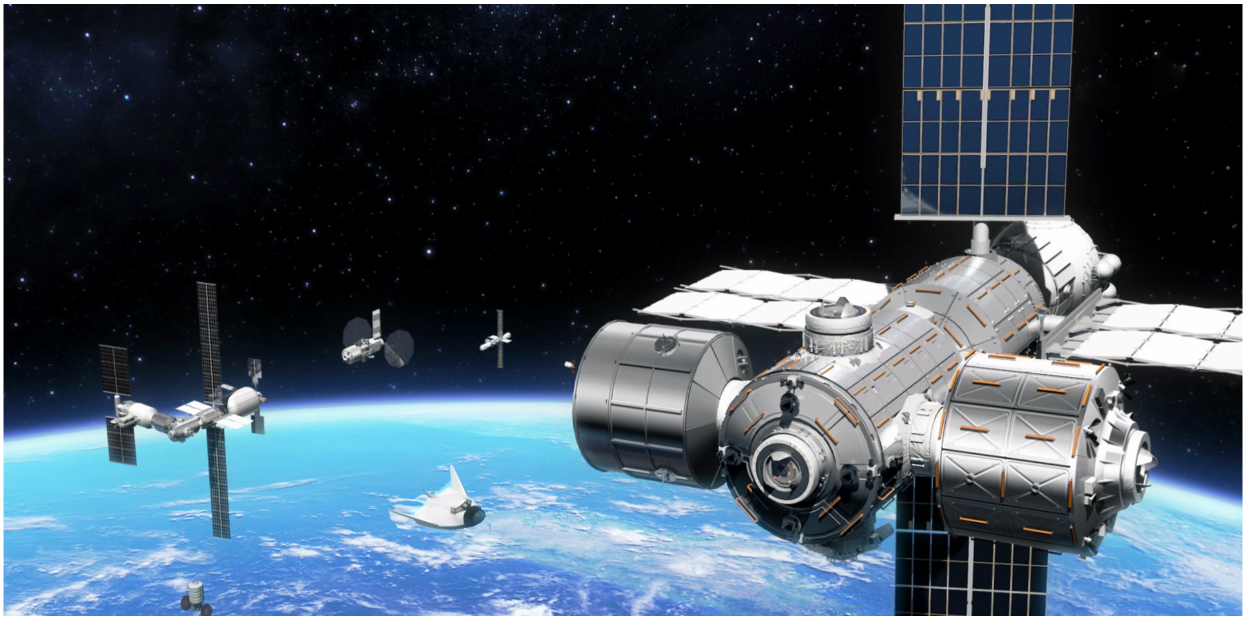
Fig. 4. DLR`s future vision for human spaceflight in LEO "Space City" (Artist`s Impression).

equipment, crew quarters and food preparation), which in turn would not be necessary to a full extent for the smaller platform saving valuable resources, which could be used for the small platform`s actual individual task.

6. Conclusions

The Orbital Hub concept is DLR`s proposal for a smooth transition between ISS and future LEO and exploration activities, which has been studied in detail including operational aspects and cost estimations. It is designed as a stand-alone solution, which could be realized with moderate budgets and timeframes thanks to its simple approach based on existing European technology in human spaceflight. Nevertheless, the modular approach of this concept is open for international cooperation and contributions of different kinds and extent. This has been elaborated by a first qualitative analysis of possible combinations between the Orbital Hub and other existing spacecraft or concepts. As an outlook, the role of the Orbital Hub as a central distribution platform in the context of DLR`s future vision "Space City" has been described.

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