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STARFAB: Concept of Operations and Preliminary System Definition for an Orbital Automated Hub and Warehouse Unit Supporting In-Space Operations and Services

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Abstract

Currently constrained by short operational lifetimes and minimal on-orbit support infrastructure, service satellites hold significant potential for future commercial and sustainable space services.

To support these in-situ services, this paper introduces STARFAB as an innovative concept for an automated orbital hub and warehouse units. The primary goal of STARFAB is to provide essential infrastructure for On-Orbit Servicing and In-Space Assembly and Manufacturing operations. It aims to enable the storage, maintenance, inspection, refuelling, testing, recycling, assembly, and manufacturing of spacecraft components directly in orbit.

STARFAB's architecture consists of a modular space station with a central linear structure. Modular secondary units dedicated to specific functions, such as storage, refuelling, or manufacturing, are attached to this primary structure. A large external robotic arm assists in handling spacecraft, secondary units, and payloads. Smaller internal robotic manipulators perform tasks within the station, while a rail-based shuttle system transports payloads and robotic agents.

Key technologies include standardized robotic interfaces (HOTDOCK) for modular assembly and reconfiguration, a dedicated robotic module (MIM) for automated inspection and maintenance, and standardized modules for the storage of components and payloads, facilitating efficient robotic manipulation.

Application scenarios range from short-term missions, such as orbital replacement units and fuel resupply, to long-term operations involving the assembly of telescope mirrors, additive manufacturing of large structures, and debris collection.

In conclusion, STARFAB offers a promising infrastructure solution for the sustainable development of the space sector, providing robotic, in-orbit capabilities for storage, maintenance, and reuse of space resources. Future work will focus on refining the warehouse function design and developing a terrestrial demonstrator.

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Keywords: New Space, OOS, ISAM, ISOS, Space logistics, Space robotics

Acronyms/Abbreviations

Concept of Operations (CONOPS), European Robotic Arm (ERA), Geostationary Orbit (GEO), In-Space Assembly and Manufacturing (ISAM), International Space Station (ISS), Life Extension (LE), Low-Earth Orbit (LEO), Medium Earth Orbit (MEO), Maintenance and Inspection Module (MIM), Non-Destructive Testing (NDT), On-orbit Servicing (OOS), Orbital Replacement Unit (ORU), Technology Readiness Level (TRL).

1. Introduction

The space sector is continuously evolving towards a model based on agility and innovation known as New Space or Big Space [1]. Therefore, accessing space has become easier, increasing its exploitation and opening new business opportunities. Recent in-orbit demonstration and validation activities support the new development of dedicated servicer satellites, able to remove debris [2], refuel [3], build large structure [4] and deliver payloads to a client satellite for upgrade and life extension purposes [5].

Currently limited to a single mission with a short lifetime, these servicer satellites could be reused if supplied and maintained in orbit. As well, their payloads could be recycled and stored to be reused later on.

To concretize these operation and service perspectives in space in a commercially viable, sustainable and robust manner in the near future, the matter of in-space storage and handling of required items and resources appears as an essential piece of the puzzle.

STARFAB's ambition is to propose a novel concept of orbital automated hub as a backbone and enabler for sustainable commercial in space operation and service activities including, but not limited to, storage, maintenance, inspection, refuel, testing, recycling, assembly and manufacturing.

This paper introduces in particular the concept overview and positioning of an orbital automated hub and related robotic ecosystem, as well as preliminary system definition.

2. Mission scenario

Implementing sustainable commercial activities in Earth orbit requires not only the key technologies necessary to offer these aimed services (OOS / ISAM), but also the means to effectively ensure the (re)supply of the involved facilities. Goods and resources storage and handling in orbit, in support to OOS or ISAM, was only barely addressed so far in the perspectives and roadmaps of the main future space ecosystem and economy actors. STARFAB intends to fill this gap, by developing the enabling technologies required to handle goods in space (including e.g. modular as well as custom shapes components for assembly, raw material for manufacturing, fuel, water, etc.) with robotics and automation means.

2.1 Market Overview

The global space economy is valued at 350 billion USD today and is expected to grow exponentially over the next 3 decades. With the drastic reduction of the launch cost, thanks to the recent launcher's development,

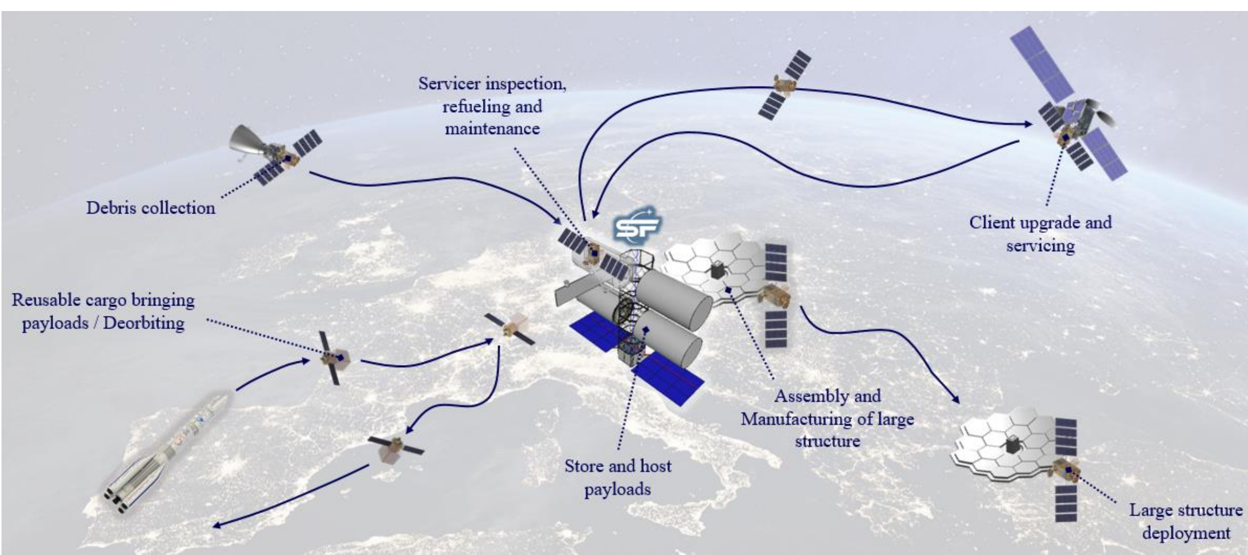

Figure 1: STARFAB's Concept Overview.

Low Earth Orbits are becoming more and more congested with operational vehicles, mega-constellations as well as space debris, and the number of satellites is expected to be multiplied. It will be crucial for the next decades to focus on a sustainable approach for the space business growth.

OOS and ISAM advancements contribute to a responsible development of space and can unlock the potential of a future circular space economy. The market forecasts for IOS $14.3B by 2030, with Life Extension driving 44% of total market revenues. The recent servicing mission prospects for satellite telecommunication operators such Intelsat demonstrate growing market confidence in LE services in GEO.

Other related activities, such as Relocation, Robotics, De-orbiting and Active Debris Removal are still affected by limited external funding and future revenue projections. By reducing the need for costly and complex ground-based manufacturing processes, re-purposing and re-using materials in space can significantly lower the costs of spacecraft production, launch, and maintenance, saving the industry $B in waste while enabling the construction of advanced infrastructure for space stations, lunar habitats, and deep space exploration vehicles. In orbit manufacturing assembly and recycling capabilities, will be needed in the long term in a circular economy and will unlock the full growth potential of in the OOS market.

For OOS and ISAM to become commercially viable, in-space storage and handling of items and resources required for these operations are critical. STARFAB introduces a novel concept, the Orbital Automated Warehouse Unit (also known as the Orbital Depot), which serves as a backbone and enabler for sustainable OOS and ISAM commercial activities in Europe.

2.2 Orbit Selection

The most promising opportunities for ISAM missions lie in LEO, which hosts the majority of satellites used for telecommunications, Earth observation, and scientific research. While ISAM is less developed here due to the lower costs of LEO satellites and the preference for replacement over maintenance, this could change with the rise of mass-produced small satellite constellations (e.g., Starlink, OneWeb). Maintenance of these medium-sized spacecraft could become economically viable if servicing costs fall below satellite replacement costs. Sustainability regulations from space agencies may further drive ISAM growth.

Large future space infrastructures, like or solar-based power plants, also offer ISAM opportunities by enabling rapid repairs and reducing service interruptions. However, LEO servicing is challenging due to the high delta-V costs for inclination changes across multiple orbital planes. Still, focusing on common orbits like Sun-synchronous orbits could mitigate this issue, and debris recycling might be an additional benefit.

GEO presents immediate opportunities for ISAM due to the high cost of satellites, but its potential is declining as the telecom market shifts toward LEO constellations. MEO is less attractive due to fewer satellites and harsher environmental conditions, while lunar, interplanetary, and L2 orbits offer long-term potential, particularly for high-value scientific missions and

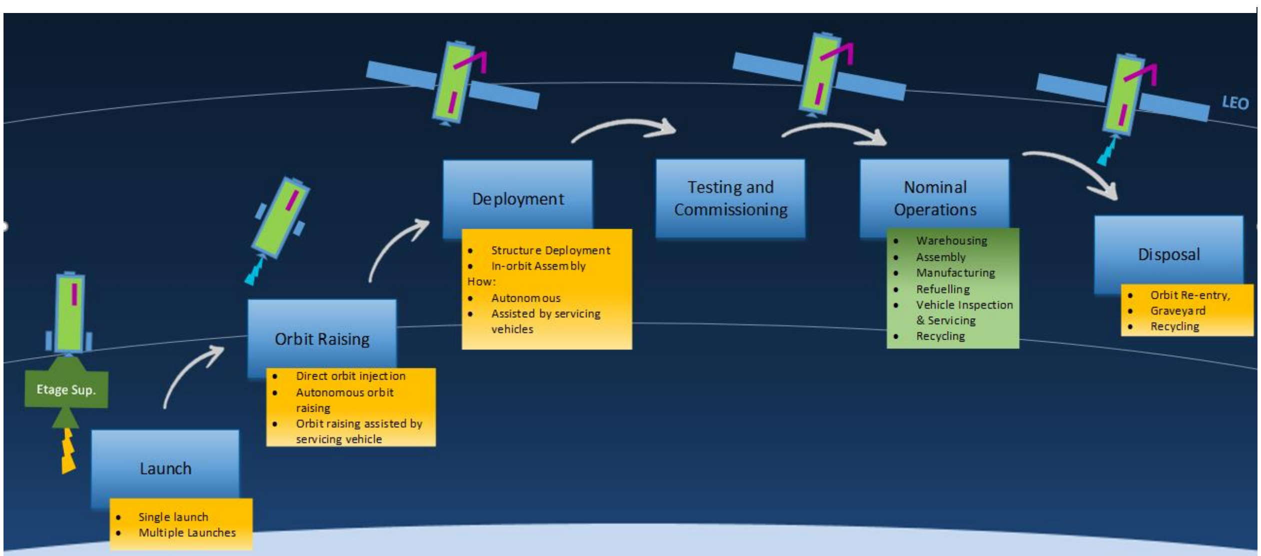

Figure 2: STARFAB's CONOPS.

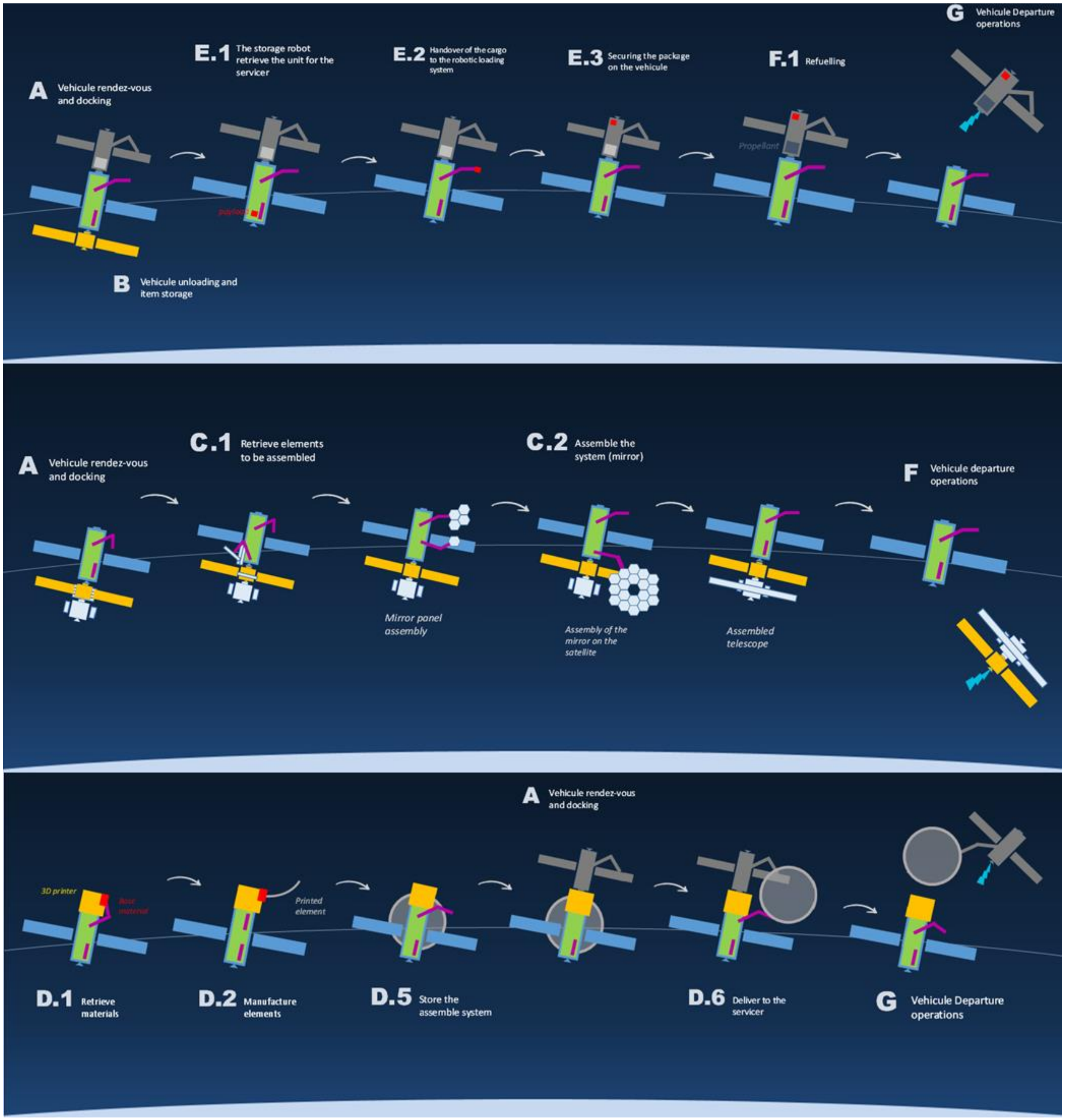

Figure 3: STARFAB's Scenarios.

human exploration programs like Artemis.

In summary, LEO offers the most growth potential for ISAM for STARFAB, while GEO and interplanetary missions represent short- and long-term opportunities, respectively. MEO is less promising due to its limited market.

2.3 Concept of operations

The first operation involves integrating the STARFAB infrastructure into the launch vehicle. This depends on whether a single launch is sufficient to transport the entire structure or if multiple launches are required. It is assumed that a heavy-lift launcher, such as the SLS (95 tons to LEO), Falcon Heavy (63 tons to LEO), or Starship (150 tons to LEO), will be available to deploy STARFAB into LEO in a single launch. However, the design may include a modular structure, allowing for future upgrades through the addition of functional modules.

After launch, orbit-raising manoeuvres will be conducted to achieve the final orbit, depending on the launch vehicle's injection point. If the vehicle performs a direct injection into the target orbit, there would be no need for additional propulsion systems or external servicing vehicles for this operation.

Due to the volume constraints of the launcher, STARFAB cannot be launched in its final operational configuration. Instead, it will be packed to fit within the accommodation volume. Once in orbit, deployment and assembly operations will begin, including the deployment of solar arrays, radiators, and structural components. These operations can be performed autonomously, using on-board robots, or by external servicing vehicles.

Upon reaching its final orbital configuration, STARFAB will undergo final testing to ensure all systems are fully functional. At this point, operational responsibility will transfer from the manufacturer to the STARFAB operator.

STARFAB’s nominal operations include several key activities:

- Warehousing: Encompasses cargo handling, loading/unloading, storage, and servicer loading.
- Assembly: Involves assembling large structural elements or spacecraft components, retrieving and delivering cargo to the assembly unit, and transferring assembled elements to servicers or client vehicles.
- Manufacturing: Includes raw material retrieval, preparation of manufacturing equipment (e.g., 3D printers), production of components, and delivery of the finished product to the client.
- Refuelling: Involves retrieving propellant tanks or connecting refuelling interfaces to client vehicles, transferring fuel, and disconnecting for departure.
- Vehicle Inspection and Servicing: Covers vehicle connection, inspection, identification of replaceable components, and servicing operations.
- Recycling: Involves retrieving materials or subsystems for recycling, conducting refurbishing or foundry operations, and storing materials for future reuse.

At the end of the STARFAB mission, disposal operations will be undertaken. Several options are available, including controlled orbital re-entry, transfer to a graveyard orbit, or recycling of the station components.

2.4 Scenarios

To assess the most likely scenario for STARFAB, a trade-off analysis has been conducted. The trade-off analysis evaluated various in-orbit scenarios based on five critical criteria: market success likelihood, technical complexity, time to market, development cost/benefit ratio, and sustainability. In the in-orbit servicing category, both delivering an Orbital Replacement Unit

(ORU) and Refuelling emerge as highly viable near-term options, demonstrating strong market potential, low technical complexity, and relatively rapid time-to-market. These attributes make them favourable candidates for short-term space industry initiatives. In contrast, within in-orbit assembly, the Assembly of a Telescope Mirror stands out as the most attractive scenario due to its higher likelihood of market success, moderate technical complexity, and a favourable development cost/benefit ratio, surpassing other assembly options such as satellite component assembly. At long term, Additive Manufacturing of Large Structure Elements and debris collection shows the greatest promise, given the anticipated market opportunities for large space infrastructure and recycling in the coming decades.

3. Preliminary System Definition

3.1 Overview

STARFAB preliminary design, illustrated in Fig. 4, is a space station concept featuring a modular and multifunctional design, based on a linear central beam architecture. The primary structure serves as the central framework supporting various units. Secondary units are mounted on either side of the primary structure, serving as storage or operational modules. A large robotic arm is connected to the outer structure to assist with tasks such as assembly, repair, and transportation of equipment around the station. STARFAB features a docking bay that can accommodate several hosted spacecraft for docking, refuelling, or servicing operations. Below the main structure is the service module, which provides essential systems (communication, control, power distribution, propulsion...). Attached to it are large solar arrays, providing the station with electrical power.

Inside, STARFAB operates with the assistance of advanced modular robotic systems. Central are robotic manipulators capable of accurate tasks, allowing for payload manipulation, maintenance of docked spacecraft and the construction of large structures from stored components. Effective transportation of goods and robotic agents inside the station and between storage and operational units are guaranteed by a series of shuttle on rails.

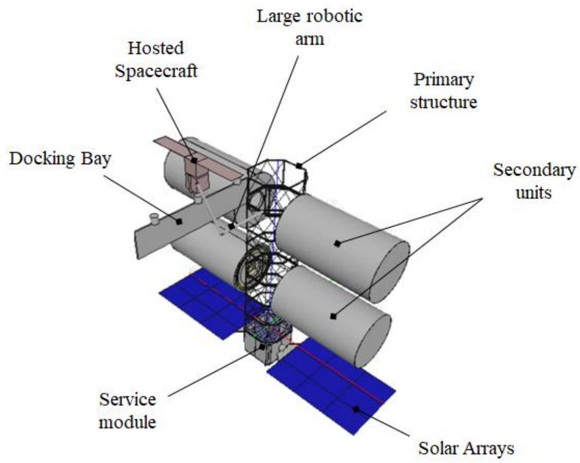

Figure 4: STARFAB Preliminary Layout.

3.2 Interfaces, Structures and Payloads

3.2.1 Robotic Interfaces

HOTDOCK shown in Fig. 5 [6] is the selected standard interconnects for robotic units and payload inside STARFAB. It is an androgynous mating interconnects, supporting mechanical, data, power and thermal transfer. It has been particularly designed for on-orbit modular assembly and reconfiguration of spacecraft elements.

HOTDOCK simplifies the replacement of failed modules and allows for payloads swapping. At the same time, HOTDOCK provides chainable data interfaces for multiple module configurations and can be used as anchor points and end-effector for the robotic systems.

Figure 5: HOTDOCK interconnects.

Outside STARFAB, it is assumed that a large arm operates thanks to latching end-effector, similarly to the Canadarm2 and ERA on the ISS.

3.2.2 Primary Structure

The primary structure is an open and monolithic mesh equipped with large Berthing and Docking Mechanisms on its sides to host secondary units as function of the needed configuration. This structure is internally equipped with longitudinal rails for accommodating shuttles and small standard interfaces for hosting small robotic manipulators, and externally equipped with a series of grapple fixtures as anchor point for the large manipulator. The primary structure connects to the service module and features a docking bay composed of 3 slots for cargos or servicer spacecraft. The docking bay also features small standard interfaces and grapple fixtures for enabling maintenance and servicing by either large or small robotic manipulators.

3.2.3 Secondary Unit

Secondary units are modular structures that can be connected to the primary structure by means of large Berthing and Docking Mechanisms. These units aim to host and deploy systems or payloads dedicated to a specific function of the STARFAB station (e.g. warehouse, fuel tank, manufacturing, assembly, recycling, outer experiment bay). In STARFAB, the development focuses on the design of warehouse secondary units, see Fig. 6, considered as priority for short term missions.

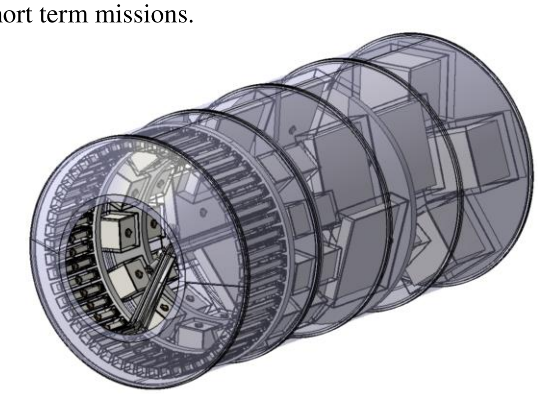

Figure 6: Artistic representation of a warehouse secondary unit.

3.2.4 Payloads

Various components, technologies and payloads are assumed to be stored within STARFAB. To keep the storing concept as versatile as possible, a standard approach has been considered by encapsulating them in predefined and standard volumes defined as multiple of CubeSat unit.

To be manipulated and transported by robots inside the station, these modules are featuring at least two standard interconnects (HOTDOCK).

3.3 Robotics Subsystems

3.3.1 Manipulation

To operate the station, STARFAB is relying on small (~2m) and large (~20m) robotic manipulators. The outer structure of the station is equipped with a unique large manipulator, similar to the Canadarm2, supporting the spacecraft docking with the station, the installation of secondary units and large payloads and supporting the transfer of small manipulators outside the station for installation and maintenance. The inner station features a series of small manipulators supporting the manipulation, transportation and transfer of payloads, as well as the maintenance. These manipulator, depicted in Figs. 7 and 8, are based on prior developments related to on-orbit servicing [7] and assembly of large structure [8].

Figure 7: Relocatable robotic arm for in-orbit servicing.

Figure 8: Multi-arm modular robot for large telescope assembly.

3.3.2 Transportation

A shuttle equipped with HOTDOCK standard interconnects is designed to operate on the rails featuring the primary structure and secondary units. This enables it to carry either a robotic system or a payload with HOTDOCK interconnects, allowing ORUs to move along the station without requiring a manipulator for transport. It is also planned that a walking manipulator can lift the shuttle off the rails and transport it to different sections of the station. For example, when the shuttle needs to be moved from one unit's rail to another.

Figure 9: Artistic representation of the relocatable robotic arm on a shuttle.

3.3.3 Maintenance and Inspection Module

To perform inspection and maintenance both inside and outside the station, a dedicated robotic module called MIM is proposed. The MIM provides automated inspection as well as routine and light maintenance. As STARFAB manages modular spacecraft components in orbit, the MIM assists in detecting and diagnosing damage or malfunctions in the station’s systems. It utilizes Non-Destructive Testing (NDT) methods to evaluate material conditions and predict failures. While NDT methods are well-established, space environments present unique challenges, as robots must perform these tasks remotely in harsh conditions. The MIM is equipped with Standard Interconnects, allowing it to be transported by relocatable robotic arms.

4. Conclusions and Perspectives

This paper presents a novel and multifunctional orbital facility, operated by robotic systems, for supporting the expansion of commercial activities in space, advancing space technology and infrastructure, and ensuring the long-term viability of human space presence. Future work will focus on the detailed design of the warehouse function of such an orbital hub facility together with its ground representative demonstrator (TRL4).

Acknowledgements

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