THE VISPA ROBOTIC MANIPULATOR - A VERSATILE IN-SPACE AND PLANETARY ARM TO SUPPORT A NEW SPACE ECOSYSTEM

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ABSTRACT

Over the last few years, a space resurgence is underway. As new missions and services are being conceived, new use-cases are taking shape to address a range of novel scenarios including active-debris removal (ADR), in-space servicing and in-orbit manufacturing and assembly. Robotics plays a crucial role in enabling and accelerating these missions. Since 2019, Airbus has been working on the development of VISPA, the Versatile In-Space and Planetary Arm, a modular robotic arm designed for next-generation space tasks such as servicing, assembly, and active debris removal. This manipulator features a slender 6 Degrees of Freedom (DoF) configuration with a reach of 2 meters long and a dextrous spherical wrist. With a mass of 17 kilograms, it is stowed into a compact volume convenient to support a range of applications on the side of a spacecraft or as part of an orbital factory.

This paper introduces VISPA, discussing its architecture, design, and current development status. It also explores future applications and services requiring the building of large infrastructures, such as space-based solar power and large antennas, and the inherent pressure put on robotic system to operate reliably at high-duty cycle over extended periods of time. To address these challenges, the discussion introduces a unique design option to service the manipulator in-flight, by exchanging modular joints should they develop a fault. This approach not only shift the design and operation paradigms by enabling the servicing and reconfiguration of robotic assets, it also significantly redefines the cost paradigms by moving away from monolithic robotics towards robotics as a consumable. The paper concludes with a discussion on potential In-Orbit Demonstration opportunities including the DEMARLUS concept aiming at assembling a small spacecraft and its antenna in space.

1. INTRODUCTION

Over the last few years, a space resurgence is underway. As new missions and services are being conceived, new use-cases are taking shape to address a range of novel scenarios including active-debris removal (ADR), in-space servicing and in-orbit manufacturing and assembly. At the core of these scenarios, robotics becomes an enabler, a cornerstone that accelerates the implementation of these missions. While a variety of manipulators are now available at the International Space Station, these products are expensive, a reflection of the design choices to address their operational use-cases at the ISS. However, to support emerging markets and novel mission concepts, these costs would be prohibitive, and a strong barrier to these commercial endeavours and the ecosystem that will enable new missions, infrastructures and markets.

Since 2019, Airbus has been developing VISPA, the Versatile In-Space and Planetary Arm, a modular multipurpose robotic arm targeted at next generation space activities such as servicing, assembly, ADR, and ultimately future planetary activities. Building on past activities including the LARAD [1] and RISMA manipulators, this development focuses on the design and implementation of a new manipulator that can bring cost-efficient robotics and sustainability to future in-space activities: a new building block in this nascent ecosystem.

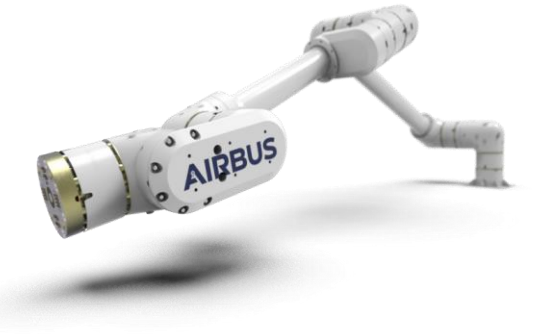

Figure. 1 – VISPA Overview

The following sections start by introducing introduce the VISPA system from an architecture and implementation point of view. As the project is on course to reach TRL6 in Q4 23, the discussion looks back at the development journey and the testing activities performed with the current models. However, looking ahead to the range of future applications and the need for robust solutions to support high-duty cycle operations, the VISPA joint swapping configuration is introduced and discussed in the context of an evolving landscape that will require a range of robotic elements to enable new mission concepts and services.

One such concept is an Orbital Factory, able to assemble a range of structures and spacecraft across its lifetime. The DEMARLUS IOD concept, featuring 2 VISPA manipulators, addresses these challenges head on by planning the assembly of a representative spacecraft and its antenna in-orbit as part of a scalable concept.

2. OPERATIONAL CONCEPT AND ARCHITECURE

Background

Over a number of years, Airbus has been developing a number of manipulators demonstrators to increasingly create a set of building blocks that can be readily reused to instantiate robotic manipulators at varying length and payload capabilities to target a range of applications. One such development is the LARAD Lightweight Advanced Robotic Arm Demonstrator [1] that featured 6DoF for a reach of 2m and a payload capacity of 7kg at full extension in 1g. The arm featured titanium Additive Layer Manufactured (ALM) structures and Ti-SIC metallic composite limbs.

The resulting manipulator mass was 16kg, providing a payload to mass ratio of 0.44. This development led to the definition of a family of high gear ratio joints at different sizes that allowed the production of several arm models reusing various joint size combinations. As part of this process, several joint sizes were identified that provided a “sweet spot” between mass and performance for the range of scenario considered. One of which is carried though in the VISPA activity as part of a design evolution with a more dynamic and low-gear implementation.

Operational Scenarios and design drivers

Throughout Airbus’s past involvement in defining space and planetary robotic applications, a range of key design drivers have been considered while investigating a manipulator solution versatile enough to address a range of applications e.g.:

- **Length** - will dictate the ADR/servicing inter-spacecraft distance and reach space, as well as the build workspace for assembly tasks
- **Stowage volume** – will dictate accommodation geometry on platform panels. Smaller/flatter volumes may facilitate accommodation for some applications, especially if multiple arms need to be accommodated.
- **Degrees of freedom** – Typically driven by the application, but 6DoF provide a dextrous enough baseline configuration, with option to select higher or lower DoFs.
- **Payload capability** – the definition of a payload vary with the application and is expected to range from the assembly of small parts to the handling of a ~1000+kg spacecraft.
- **Accuracy and repeatability** – Again, this will be application dependent, however in relative terms, part assembly and servicing will require higher accuracy versus ADR. However, several control techniques including visual servoing can be used to improve locally the accuracy of the manipulator.
- **Mass** – Lighter configurations will facilitate accommodation to a wider range of platforms and minimise launch costs.
- **Operation in 1g** – Highly desirable if possible to perform representative functional tests with a flight configuration, especially without dedicated gravity offloading. However, this will affect the arm joint sizing and actuator margins and the accuracy of the manipulator unless a suitable gravity compensation system and calibration is implemented.

Kinematic design

Although the system is modular, the baseline kinematic design is based on a 6DoF configuration (R-P-P-R-P-R) with a spherical wrist, providing good dexterity while enabling the use of an analytical closed-form inverse kinematics (IK) solution. This allows the resolution of the IK without the need for iterative solvers and provides an option to process the IK on very low power processing units. The extended configuration reaches 1955mm at the end-effector interface.

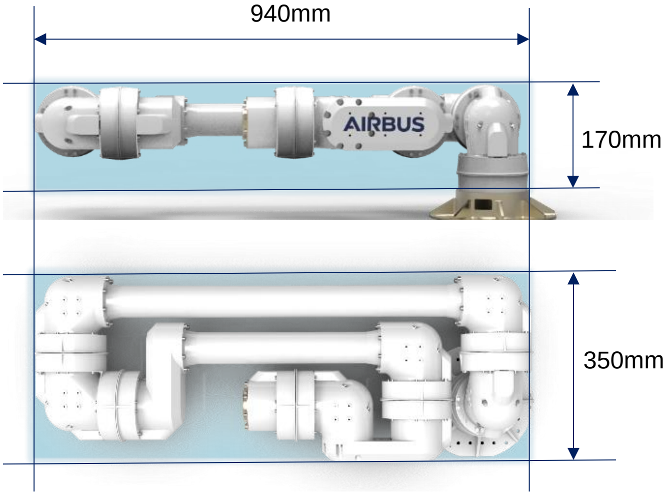

Figure. 2 – VISPA baseline configuration

Electrical architecture

The electrical architecture significantly drives the design and implementation of the arm as well as the selection of the technological solution implemented as part of this concept. Early trade-offs were performed to evaluate the benefits of centralised and decentralised motion control against the size and complexity of the harness routing, motor technology selection, joint mass, modularity and scalability. Ultimately, a distributed setup was selected with in-joint drive electronics to enable the use of DC brushless motors while minimising the harness size and sensors noise. This option provides the minimum harness solution and enables the design of

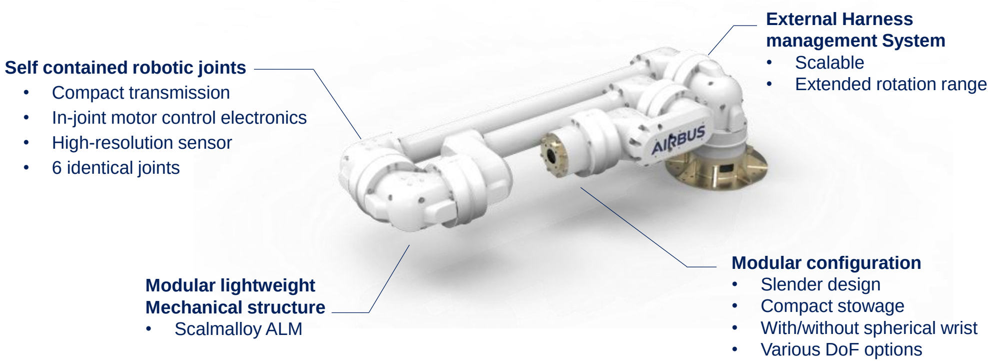

Figure 1 – VISPA Design Overview and Key Features

of identical joint and electronics without the need for specific customisation. The driving electronics are then daisy-chained on a data bus to the Robot Control Unit (RCU). This architecture readily allows the implementation of various DoF arms with the same joints design.

To date the baseline VISPA configuration implements a redundant CANbus to service the joint drive electronics and the end-effector. A dedicated high-speed Spacewire (or Ethernet) link can be implemented to service high bandwidth end-effector sensors such as cameras.

The joint units are self-contained and comprise the joint structure, BLDC motor, drive electronics and sensing (motor side and joint output sensors). Pending on the use-case, various redundancy options are possible. The driving electronics for the VISPA manipulator have been designed around a distributed processing architecture where all low-level control is provided locally, while only high-level commands are being transmitted by the RCU. As part of the design philosophy targeting a robust but cost-effective solution, careful part selection has been performed to selectively implement rad-hard components, rad-tolerant, or high performance components with shielding and/or redundancy.

Harness management system

Based on past experience of harness design and integration along robotic arms, the project came with a desire to streamline the integration process by parallelising the integration of the mechanical element while the harness can be produced and tested prior to fitting on the structure. To this end, unlike a number of past and ongoing manipulator developments, VISPA features an external harness management system at the joint that deals with the routing of the cables during the joint actuation. The selected concept, features a compact cable drum around the body of the joint that allows each of the joints to physically cover in excess of +300° to -200° of motion.

Mechanical design

The structure of the manipulator consists of bracket structures made of additive layer manufactured (ALM) Scalmalloy. Scalmalloy® is a high-performance alloy developed by Airbus made from scandium (Sc), aluminum (Al) and magnesium (Mg) alloy. It is the only additive manufacturing alloy which substitutes for high strength 7000 series aluminium alloys with yield strength in excess of 475MPa. This allows the production of optimised brackets that can be made lighter than other aluminium alloys, while using less material. The ALM process has offered significant design flexibility to produce and evolve the design across a number of iterations. The limbs themselves are made out of a single piece of aluminium.

3. DEVELOPMENT PHILOSOPHY AND STATUS

Unlike a typical waterfall development that follows a set of design and implementation steps up to a finished product, the VISPA development philosophy has followed instead a set of tight design iteration cycles whereby improvements on components are fed back into the design baseline at the first opportunity.

DM developments

The DM TRL4 model configuration was built from the ground up following a number of design processes more representative of more mature models and using components as close as possible to their space equivalent. This approach provided a mature DM model, providing early on form, fit and function for the target application.

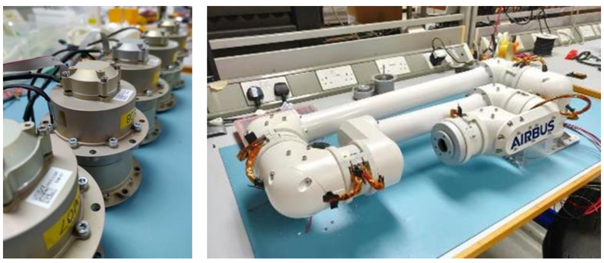

Figure 2 – VISPA TRL4 DM Joint and DMv1 manipulator

TRL5 developments and design iterations

As the DMv1 was built, tested, and exercised, lessons learnt were systematically compiled to record improvement to all aspects of the build, including parts complexity, parts count, material selection, integration complexity, joint characterisation, tuning process, control, etc. This led to a number of design iteration and optimisations that were folded in as part of a TRL5 joint, subjected to a TVAC test campaign to characterise the operation of the joint in a space representative environment. Upon successful completion, a number of the TRL5 design iterations were retrofitted to the TRL4 model, evolving it to a DMv2 model

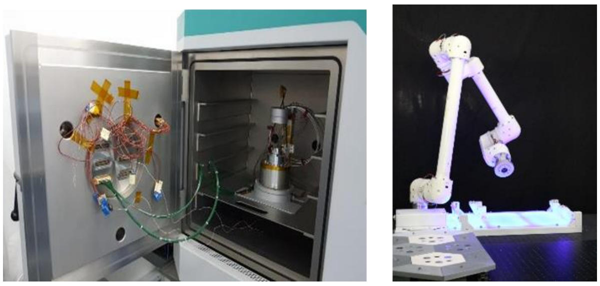

Figure 3 – VISPA TRL5 joint testing and manipulator DM v2

TRL6 design evolutions

Following the same development process, a range of design iterations have been identified based on the lessons learned from the TRL5 design, and the continued use of the DMv2 model across a number of use cases, leading to the current EM design, poised for TRL6-level testing including TVAC, and vibration testing to be completed in Q4 23.

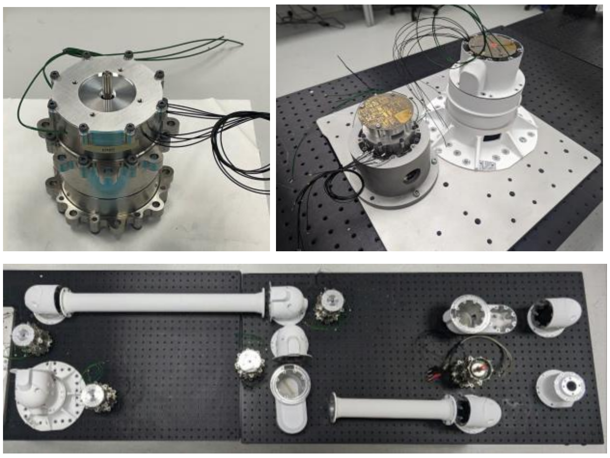

Figure 4 – VISPA EM integration

4. CONTROL

To facilitate the operation of the manipulator and the execution of specific tasks, the control architecture features a number of control modes designed to provide the low-level granularity to perform joint-space, and task-space control, as well as higher level control mode.

The higher-level modes, developed by Airbus GmbH, focus on the implementation of functions to enhance manipulator safety and increase accuracy. To increase safety, admittance and impedance control modes are implemented as a mean to provide the manipulator a proprioceptive detection of interactions with its environment, providing added safety during operation, for the manipulator and its surroundings. To enhance the accuracy of the manipulator to fulfil the task at hand, visual servoing is used.

Visual Servoing

Space manipulators will increasingly be required to perform complex and precise tasks requiring accurate positioning of the Tool Contact Point (TCP). From servicing operations to assembly of future large infrastructure, the quality of the final assembled product is directly impacted by the accuracy of the robotic operation. While terrestrial industrial robots feature sturdy structures and multiple sets of high-resolution sensors, space manipulators will be more slender, lightweight and will be subjected to a harsh environment and a broad range of thermal conditions. All of these aspects will affect the placement of the TCP and its final accuracy to perform the task. On top of that, if there is a desire to perform testing in 1g, additional structure and joint flexures will be experienced, affecting further the TCP placement.

To remediate these challenges, extensive testing was performed in [2] to develop and evaluate a set of a visual servoing techniques including Look-Once and Move (LM), Iterative Look and Move (ILM) and Feature-Based Servoing (FBS) amongst others. As part of this wide-ranging testing process, the VISPA manipulator was pitted against a KUKA iiwa R7 as a representative of a mature industrial cobot. The tests and their results are quite relevant as they involved the VISPA DMv1 that featured a “softer” joint configuration, more sensitive to 1g testing.

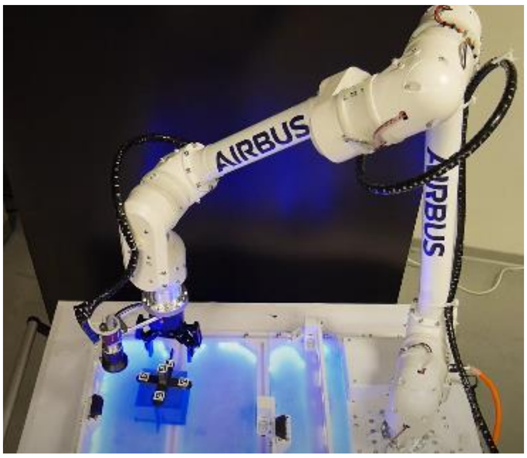

Figure 5 – VISPA visual servoing test setup with a camera at the end-effector tracking markers

The test process involved the placement of the arm end effector based on a set of fiducial markers identified by a camera close to the tool. A laser tracker provided accurate recording of the ground truth to compare the two manipulators controlled though the various algorithms.
The outcome of the testing concluded that in the tested configuration, VISPA intrinsic repeatability was in the order of 0.33mm/0.05º against KUKA's 0.18mm/0.03º. Implementing visual servoing techniques to place the end-effector, high accuracy was achieved, well below 1mm positioning accuracy and smaller than 0.05° orientation. Both of which well compatible for assembly and precise tasks.

5. TESTING ACTIVITIES

A number of testing activities were undertaken to evaluate some of the use-cases expected of the manipulator and tested in 1g. These included a planetary trenching and sample collection scenario, an assembly scenario and ADR emulation.

Use-Case 1 – Trenching and sample collection
This scenario emulated the trenching in a planetary surface and the collection of regolith for a secondary process (e.g. analyses or ISRU). The tests investigated the behaviour of the manipulator as it trenches in the various soils and the various motions required to maximise sample collection with a passive scoop (angle of insertion, rotation and lift) and sample deposition in the receptacle.

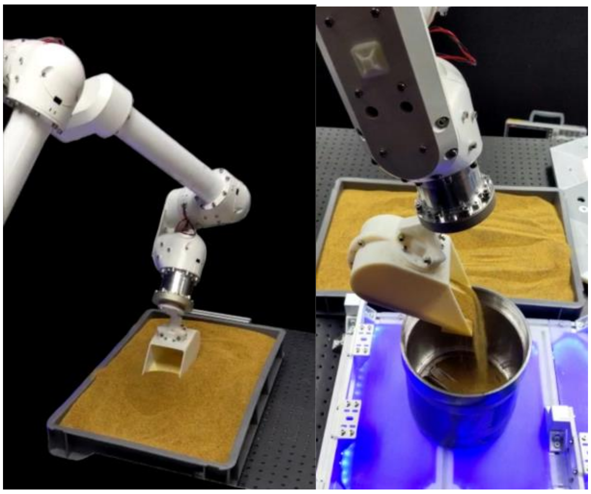

Figure 6 – Use-Case 2 – Trenching and regolith collection

Use-Case 2 - Assembly
The H2020 PERIOD project [3] investigated the design of an in-space factory where a set of components were assembled to form a reflector that was fitted onto a small spacecraft. The laboratory setup emulated this scenario by setting up a set of parts and tiles (albeit scaled down) that were assembled in a tight-fitting structure as part of a pick and place scenario. This scenario was conducted without visual servoing to characterise the behaviour of the manipulator over these repetitive tasks, and its ability to pick parts across its workspace to assemble/insert them.

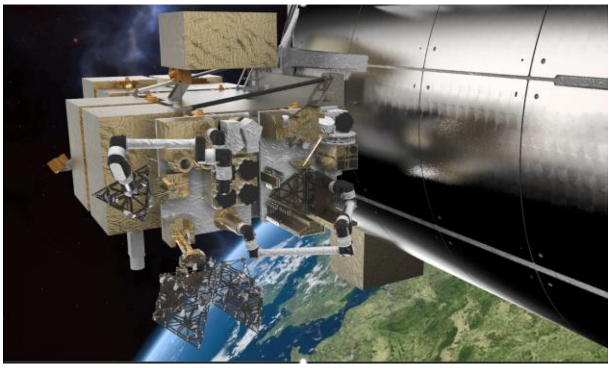

Figure 7 – Use-Case 1 – H2020 PERIOD in-space assembly factory [3]

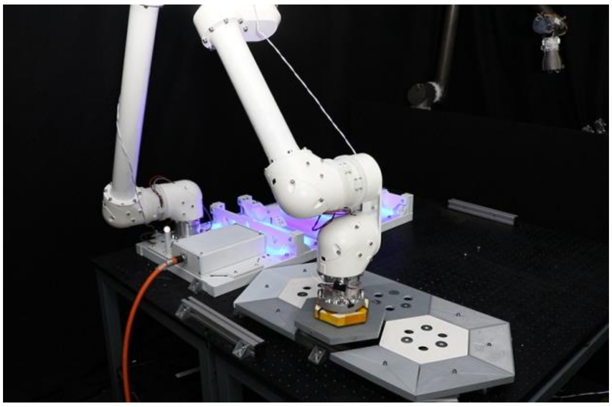

Figure 8 – Use-Case 1 –Parts assembly into a mock up structure

Use-case 3 – Active Debris Removal/ Servicing
Space sustainability comes in several guises, whether by managing debris to ensure continued and safe access to space, or by providing the means to extend the lifetime of missions either through servicing, refuelling or payload upgrades. Robotics is expected to play a significant role in fulfilling some of these objectives and VISPA is being designed to address these use-cases as a valuable technology block in this emerging ecosystem of missions, systems and services.

To investigate these scenarios, a test campaign was undertaken with the Satellite Catapult IOSM facility in Wescott, UK, to investigate a representative ADR/ servicing scenario with the VISPA manipulator. The setup involved a representative servicer with the manipulator, and a target spacecraft. The campaign had two primary objectives: the approach and inspection of the target while simultaneously tracking its fiducial markers, as well as the approach, grasping and released of a mock-up launch adapter ring.

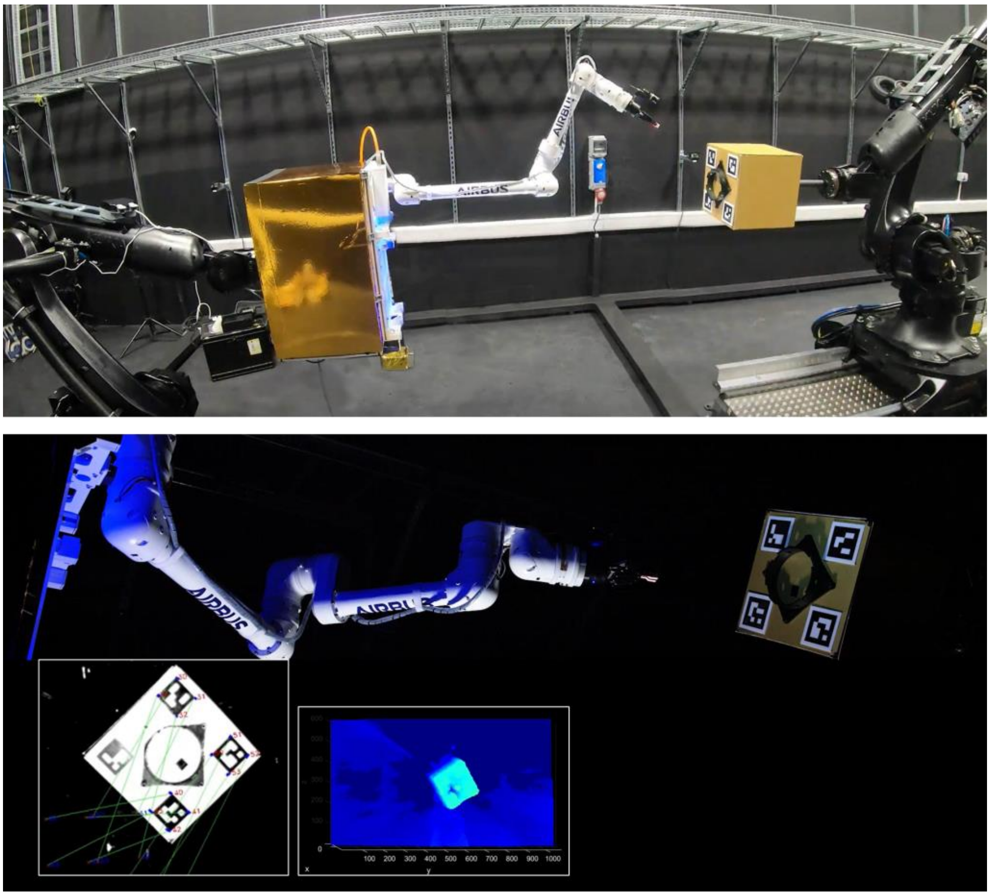

Figure 9 – Use-Case 3 –Active Debris Removal and Servicing (video in [4])- Test Setup at the facility (top), actual test (bottom) with active marker tracking (left) and resolved distance map (middle)

This campaign also served as a pathfinder project in preparation of future test campaigns at the facility with future mature manipulator models.

The campaign was successful and exercised the manipulator at full stretch in a workspace representative of the use-case. Various strategies have been implemented to identify the best approach to operate in 1g and maximise the representativity of the operations.

6. SUPPORTING LARGE STRUCTURE ASSEMBLIES – REPAIRING ROBOTS IN SPACE

As we look ahead to the future assembly of vast infrastructures in space such as antennas and space-based solar power, it is necessary to acknowledge that these scenarios will require high duty cycle operations over extended periods and in harsh conditions. This will invariably affect the lifetime of the robotic system. These missions, however, will be highly dependent on the robotic system that must demonstrate high dependability and continuity of service over the mission lifetime. To this end, two design and implementation paradigms are available. On the one hand, a monolithic robotic system (the default to-date) can be designed to be hyper-redundant, with very reliable and complex parts, and subjected to extended testing regime. This approach will be expensive and does not necessarily prevent the system from failing, ultimately affecting the mission operation. On the other hand, it is possible to start with the premise that, over the mission lifetime, at least one robotic joint will fail. Accepting this assumption then shifts the emphasis from a design built to provide fault prevention and avoidance, to a design focused on fault mitigation and active recovery. To this end VISPA is introducing a patent-pending configuration with serviceable robotic joints that can be exchanged robotically.

The modular design of the VISPA manipulator with 6 identical joints allows it to explore new operational scenarios where some of its joint can be removed and replaced. This setup is particularly relevant as part of a typical two-arm factory, or the three-legged mobile platforms similar to the ESA MIRROR configurations [5][6] where 2 manipulators are able to service themselves, exchanging joints that have reached their end-of-life, or developed a fault. Not only does this provide mission robustness and system dependability for critical tasks, it will also affect drastically

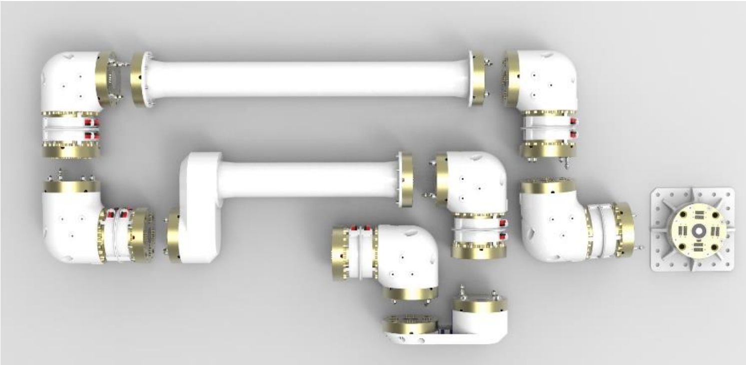

Figure 2 – VISPA-S swappable joint concept – Single-joint configuration

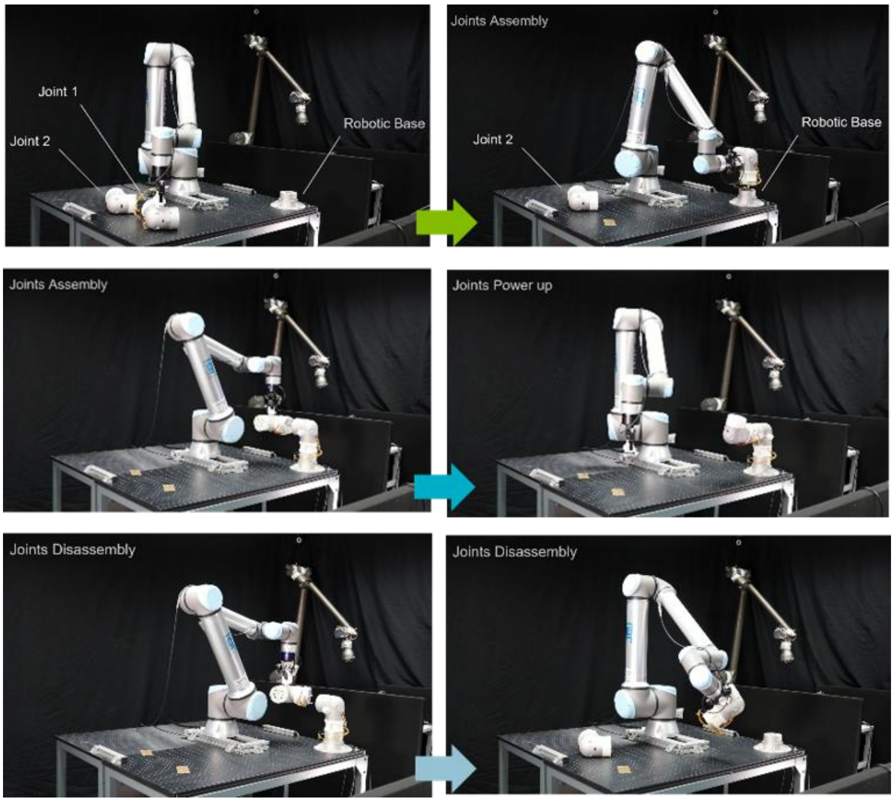

Figure 2 – VISPA swappable joint testing – Demonstrating assembly, operation and disassembly (video [7])

the economics of building these large assemblies by allowing the replacement, return, refurbishment and re-supply of fresh joints over the mission lifetime, transitioning from robotic-driven mission to robotics-as-consumable. In addition, it offers additional operational flexibility by allowing the manipulator to evolve its configuration as the mission progresses. This could include adding or removing DOF or extending limbs as the workspace or the state of the build evolves. To date, several swappable module configurations are being investigated, whether they consist of a single joint or a set of two orthogonal joints.

7. TARGET IODS

As the VISPA manipulator evolves through the higher TRLs, a number of mission concepts are being explored, enabled by robotics, addressing a range of scenario. One of these is the DEMARLUS project [8] investigated by Airbus SAS and The Exploration Company, that aim to prepare the industry and the European space community to successfully enter the future ISMA and OOS markets. With an in-orbit demonstration slated for 2027, the project aims to demonstrate the feasibility of an in-orbit assembly mission on board a reusable service module. The mission will focus on the definition of the robotic operations to assemble a reflector kit autonomously that will be assembled and tested in space.

The DEMARLUS project is currently in phase A, defining and designing the complete system, a complete simulation of robotic operations and a demonstration of the critical operations in the form of a full-scale demonstrator.

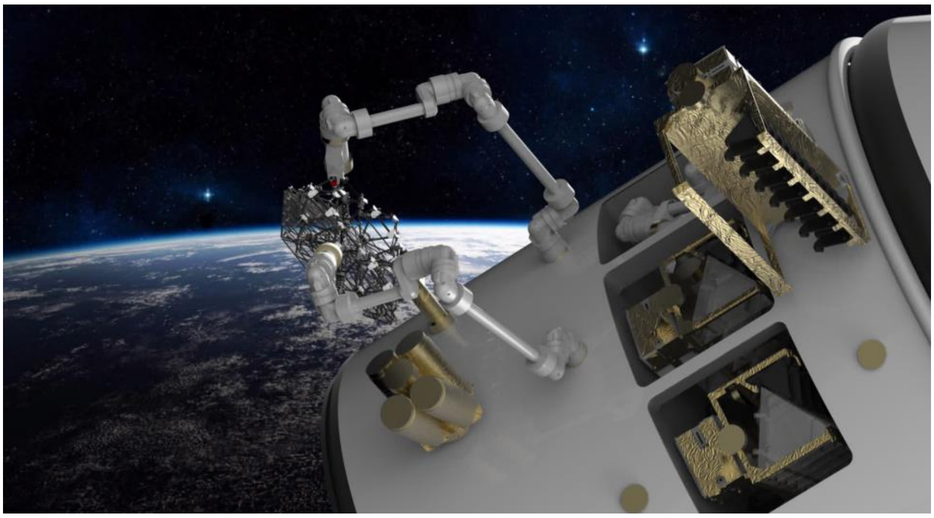
Figure 10 – DEMARLUS In-space factory IOD concept [8]

It aims to pave the way for a future in-orbit demonstration that will integrate an end-to-end chain of processes and technologies to manufacture, operate and maintain satellites in orbit including:

- Space logistics using a reusable vehicle.
- The manufacturing of elements such as an antenna reflector by robotic means overseen by a digital twin of the plant capable of integrating telemetry data in real time.
- Assembly of the satellite bus by robotic means.
- Quality control of the whole and validation of performances.
- Safe ejection of the integrated satellite into orbit.

8. CONCLUSION

New missions are being designed to address a range of novel applications, from ADR, to servicing and assembly. This emerging ecosystem is gathering pace with bold new ideas coming from across academia, SME to large primes, all of which have a role to play in developing these new missions and the technology to support them. Airbus identifies that large infrastructure assemblies will be an enabler for new services, with application to future telecoms, science, and leading potentially to vast space-based solar power concepts.

The VISPA manipulator is designed from the ground up to be a building block in this ecosystem, able to support new missions cost-effectively and possessing the unique ability to be repaired or reconfigured in-flight. As versatile system, while it is being developed to support future large-scale assemblies, it will also find direct applications to more immediate goals such as ADR and servicing.

As part of a drive to further accelerate and support this long-term vision, Airbus has open-sourced the URDF of VISPA[9]. The model is being used across a number of developments, university projects and student competitions related to IOSM activities. This approach has generated a lot of interest across the various users, able to simulate a range of in-space tasks, design new tools or control methods based on a realistic space robotic manipulator.

What appeared like bold science fiction only a few years ago is taking shape today. As new endeavours come to light, the visions for the future look even bolder but tantalisingly reachable as we develop the means to implement it.

9. REFERENCES

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