DEMONSTRATOR DESIGN OF A MODULAR MULTI-ARM ROBOT FOR ON-ORBIT LARGE TELESCOPE ASSEMBLY

Mathieu Deremetz (1), Maxence Debroise (1), Shashank Govindaraj (1), Alexandru But (1), Irene Sanz Nieto (1), Marco De Stefano (2), Hrishik Mishra (2), Bernhard Brunner (2), Gerhard Grunwald (2), Máximo A. Roa (2), Matthias Reiner (2), Martin Závodník (3), Martin Komarek (4), Jurij D'Amico (5), Francesco Cavenago (6), Jeremi Gancet (1), Pierre Letier (1), Michel Ilzkovitz (1), Levin Gerdes (7), Martin Zwick (7)

(1) *Space Applications Services NV/SA, Leuvensesteenweg 325, 1932 Sint-Stevens-Woluwe (Brussels Area), Belgium, firstname.lastname@spaceapplications.com*
(2) *Institute of Robotics and Mechatronics, German Aerospace Center (DLR), 82234 Wessling, Germany, firstname.lastname@dlr.de*
(3) *Frentech Aerospace s.r.o., Jarní 977/48, 614 00 Brno-Maloměřice a Obřany, Czech Republic, firstname.lastname@frentech.eu*
(4) *L.K. Engineering s.r.o., Vídeňská 55, 639 00 Brno, Czech Republic, lastname@lke.cz*
(5) *Thales Alenia Space France, 26 Avenue J.F. Champollion, 31037 Toulouse Cedex 1, France firstname.lastname@thalesaleniaspace.com*
(6) *Leonardo S.p.A., Viale Europa, 20014 Nerviano (MI), Italy, firstname.lastname@leonardocompany.com*
(7) *Automation and Robotics Section, European Space Agency (ESA), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands, firstname.lastname@esa.int*

ABSTRACT

The development of building blocks, and standard interconnects in particular, enables promising perspectives for the assembly of large structures on-orbit. By coupling these standard interconnects with dexterous arms, it is now possible to imagine orbital robots assembling, in-situ, modular structures to emancipate from launcher constraints.

Such a mission scenario and related concept of operations are proposed within the ESA MIRROR project. It involves a modular multi-arm installation robot to address this challenge. This paper deals with the design of a fully representative breadboard for this innovative robot in order to prove its concept and abilities. This demonstrator features a ground equivalent robotic system, a testbed and necessary ground support equipments.

1. INTRODUCTION

Space facilities for orbital exploitation and exploration missions require increasingly larger structure to extend their capabilities. Dimensions of future outposts, solar facilities and telescopes will undoubtedly matter to expand our horizons, supply on-orbit applications or explore the universe [1]. Due to the size of these structures, a single self-deploying asset contained in standard launcher fairings is inadequate. Instead, these large structures may be broken down into modules that can be assembled in-orbit. Assembling large structure in space is a major challenge but technologies such as standard interconnects and dexterous orbital robotics open new horizons for such applications [1-2]. In the presented work, we assume that the large spacecraft structure and modules are equipped with Standard Interconnects (SI) that provide mechanical, data and power transfer capabilities. The SIs allow the modules to mate to each other, and allow the robotic manipulators to capture, transport and install these modules. They are also the attachment points for the robot system, allowing it to relocate across the spacecraft structure and modules.

This paper introduces the concept of a novel Multi-Arm Robot (MAR) dedicated to on-orbit large telescope assembly (see Fig. 1), and its ground equivalent laboratory demonstrator design, developed in the context of the ESA "Multi-arm Installation Robot for Readying ORUS and Reflectors (MIRROR)" project.

Figure 1. Artist representation of the MAR concept.

To assess the MAR concept, a Technology Readiness Level (TRL) 4 breadboard has been designed. It will allow demonstrating that the multi-arm robot can execute its overall scope of operations in a ground laboratory environment. It comprises a testbed (dummy spacecraft structure, home base, storage area and mobile payloads) offering a space representative environment, a mission control centre (computer, simulator and electrical/data support equipment) supervising the MAR's tasks, and a gravity compensation system (gantry crane and offloading system) for operating the robot under 1-g.

The structure of this paper is as follows: Sec. 2 introduces the technological demonstrator. Sec. 3 presents the equivalent flight segments, while Sec. 4 describes the ground segment. Sec. 5 finally provides a conclusion on the work achieved and presents perspectives on future activities.

2. TECHNOLOGICAL DEMONSTRATOR OVERVIEW

For the purpose of the validation of the MIRROR concept, introduced in [3], a realistic 1-g breadboard system has been developed. This testbed demonstrates the tasks that will be carried out by the multi-arm robot during the assembly of a space-based structure. This will be achieved by building a 1g adaptation of a section of the telescope as shown in Fig. 2.

The items comprising the breadboard have been carried out to meet MIRROR's operational and environmental requirements. To adapt the scenario to a 1g environment some adjustments have been made. Instead of a complex 3D structure the constituent items of the breadboard are laid out in a plane. The home based is attached directly to the mirror tiles and the mirror tiles themselves are flattened. This 2D structure also has the benefit of simplifying the gravity compensation mechanism.

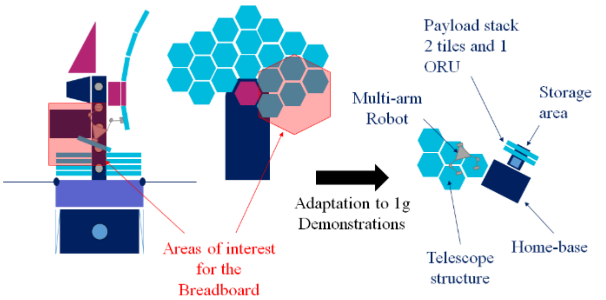

Figure 2. Adaptation of the space assembly task to the 1-g breadboard.

The proposed breadboard includes a home base, some pre-assembled mirror tiles and a storage area (or servicer) on which two tiles and an Orbit Replaceable Unit (ORU) are stored. The overall structure, tiles and ORU are equipped with SIs. The number of mobile elements has been chosen to show the scope of assembly tasks faced when assembling hexagonal tiles, involving either one, two or three SIs simultaneously.

Developed at TRL4, the MIRROR technological demonstrator, illustrated in Fig. 3, features a ground and a flight segment as follows:

- Flight segment:
  - The "Multi arm relocatable manipulator" (MAR) capable of grasping, releasing, and transporting payloads (mirror tiles and ORU). The MAR includes independent avionics to implement motion and to provide power to its actuator.
  - The "MIRROR testbed" provides the physical environment where the MAR system can demonstrate its functions in six degrees of freedom. The proposed MIRROR testbed includes a dummy spacecraft body, hexagonal telescope tiles and ORU equipped with SIs and a weight compensation device.
- Ground segment:
  - The "Monitoring and Control Station" (MCC) that allows users to supervise MAR's tasks. This ground segment involves a programming interface linked with a simulator and a task/motion planner.
  - The "Electrical Ground Support Equipment" (EGSE) or power subsystem provides power to the Control Station.

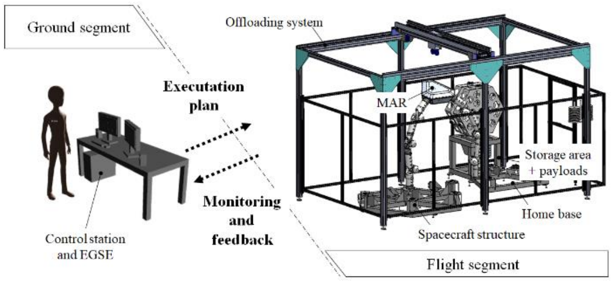

Figure 3. MIRROR's ground demonstrator concept.

3. FLIGHT SEGMENT

3.1. MULTI-ARM ROBOT

The MAR, depicted in Fig. 4, is a ground equivalent modular robot of the flight concept [3] in terms of kinematics, size and functions It is also composed of three robotic subsystems: a torso and two symmetrical 7-degree of freedom (DOF) anthropomorphic arms. The torso is the main body of the robot. This mechanical hub can equip three other appendages (limbs or payloads) or can be attached directly to the spacecraft structure. This central subsystem provides the required power and communicates high-level information to its connected modules. The torso is also equipped with vision and perception devices for monitoring purpose, and an energy storage pack in case of unavailability of other energy sources. The robotic arms are limbs that act as arms or legs depending on the desired configuration of the robot. They can be used to manipulate payloads or to relocate the robot, following the output of a suitable locomotion or manipulation planning stage. The robotic subsystems (torso and robotic arms) are functionally independent and can be connected by means of SIs (see Fig. 5). This modular approach of the MAR aims at reducing the complexity of the different robotic appendages and offers a set of robotic configurations that extends the range of possible operations and provides an intrinsic system redundancy that reduces the overall mission risk. To this end, a passivity-based locomotion controller has been designed to execute all the MAR operations for the morphologies described above. The Cartesian impedance characteristics of this controller allow a compliant behaviour in the presence of the SI constraints.

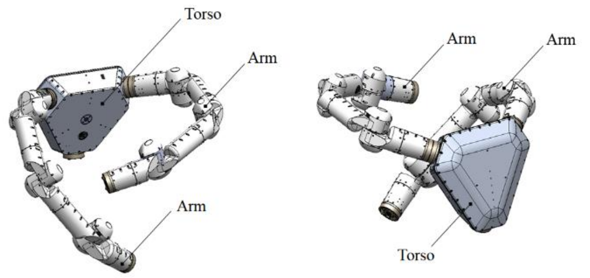

Figure 4. Detailed design of the MAR.

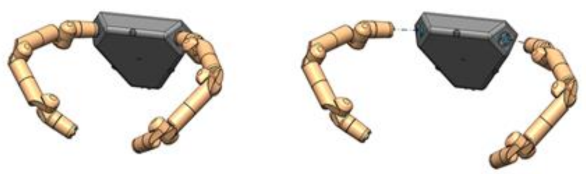

Figure 5. MAR system modular assembly: torso (grey) and robotic manipulator (orange).

3.1.1. Mechatronics design

The torso of the MAR, illustrated in Fig. 6, is composed as follows:

- Mechanical Structure – The torso is a truncated tetrahedron. Since the configuration includes two robotic arms for walking/manipulating and one attachment point for ORUs, this structure has an equilateral triangle baseline. To allow serial or parallel manipulation and relocation without restricting the workspace areas, the sides of the torso are chamfered.
- Two fixed active SI - Two of the three main corners of the torso are equipped with static active HOTDOCKs [4] on which the two "robotic manipulators" will be attached.
- One actuated active SI – as a leg (one rotation around its main axis). The third point of the torso is used for grasping payloads (mirror tiles or ORUs) or to attach to the spacecraft. This attachment point also uses a HOTDOCK. The particularity of this third attachment point is its mobility. It allows the torso to rotate the payload when performing a manipulation action or to spin itself around if it is attached to the spacecraft.
- Perception Sensors and Lighting Modules – Due to the geometry of the torso, the belly can be mostly protected from exterior illumination. This surface is equipped with a camera, at the center, and lighting modules to monitor the assembly and manipulation tasks carried out by the robot.

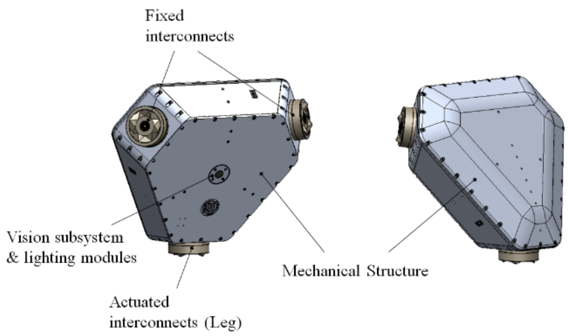

Figure 6. System overview of the Torso.

- Avionics: The torso is equipped with its own embedded avionics that implements motions, controls its leg and attached robotic arms, receive/forward power and data through its structure (see Fig. 7). The torso embeds an on-board computer (OBC), communication modules (CAN, EtherCAT, wireless), a battery (in case of power failure through the SIs), power distribution (cPDU) and converter (PCU) units, and servo control units (SCU) to control the leg and the SIs.

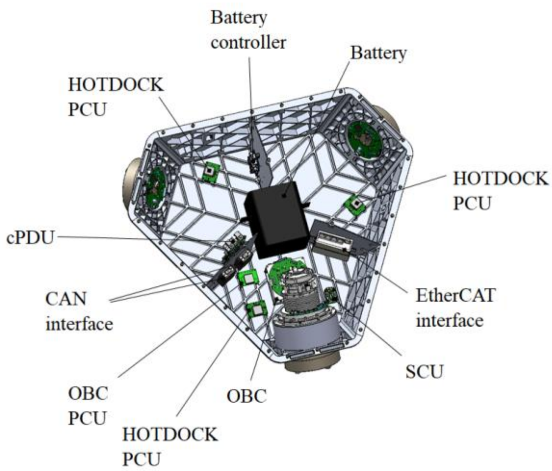

Figure 7. Integration of the avionics subsystem inside the torso structure.

The robotic manipulators, illustrated in Fig. 8, are derived from [5] and composed as follows:

- Structure (Limbs): The robotic manipulator is composed of structural limbs that mechanically link the joints with each other. The overall structure of the manipulator is based on a human-like arm with asymmetric joints.

- Motorization (Robotic joints): Revolute motors integrated into the limbs actuate the joints of the robotic manipulator. The robotic manipulator is equipped with seven revolute joints according to the following symmetric configuration R⊥R⊥R⊥R⊥R⊥R⊥R, where R indicates a revolute joint and ⊥ the orthogonality between two successive joint axes.

- SIs as End effectors: Each extremity of the robotic manipulator is equipped with an active standard interconnect, namely HOTDOCK. This configuration brings to the arm its walking and modular feature since the arm can be attached from both sides.

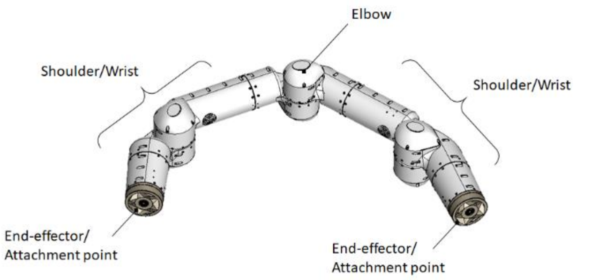

Figure 8. System overview of the Robotic manipulator.

- Avionics: In order to implement motions, control its robotic joints and receive/forward power and data through its structure, the robotic manipulator is also equipped with its own independent avionics (see Fig. 9). Each motor is controlled by a drive. Also, each arm embeds an on-board computer and communication modules (CAN, EtherCAT, wireless).

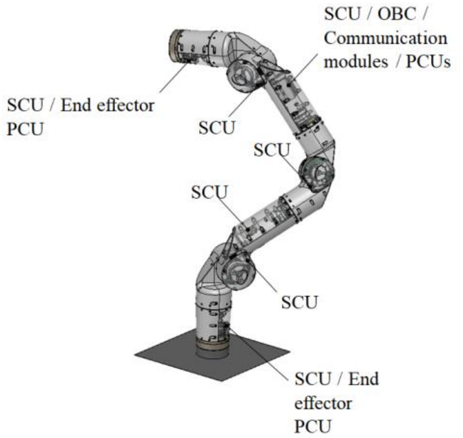

Figure 10. Integration of the avionics subsystems inside the robotic manipulator structure.

3.1.2. Software architecture

The Multi Arm Robot (MAR) control system includes three layers, which are described as follows:

- The low-level controller layer with the EtherCAT communication stack for commanding each robot joint drive.
- The control-software layer to enable/disable the MAR motion and set the position or torque commands based on advanced control methods (e.g. Cartesian Impedance Controller)
- The path planning layer, which delivers a sequence of actions, representing the motion of the manipulator system as well as the system configuration used to perform the desired operation and the commanding of the SI.

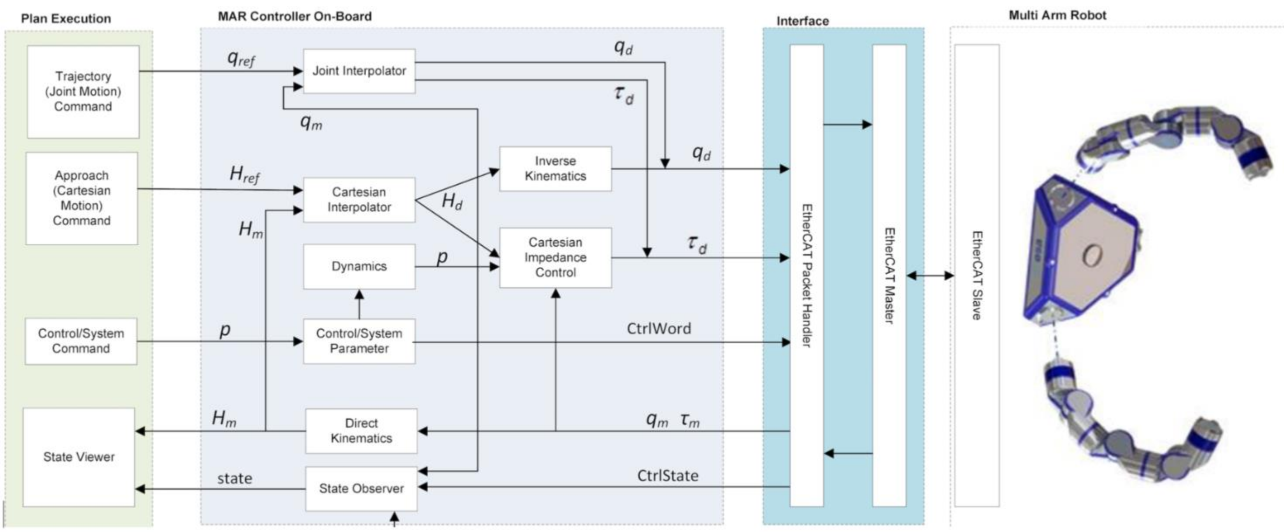

Figure 9. Control Software architecture.

All the components to control the MAR system from low-level-control to high-level control are shown in Fig. 10.

The planning interface receives the current state from the MAR via the MAR controller on the OBC and uses the description of the task that the robot has to execute to provide the desired trajectories to the control-software. These trajectories guarantee feasibility of the task under motion constraints, e.g. collision and singularity avoidance. Finally, the planner also receives operation status and flags from the control-software for monitoring purposes and to detect the need for re-planning.

Each joint drive is equipped with a low-level control-software running on the SCU. It has an implementation of the EtherCAT communication interface, and the motor drive setpoint controller, which are commanded by the control-software layer for all the joints in unison. The low-level controller has two modes of operation: torque and position. Each mode corresponds to the signals sent by the control-software layer, i.e. desired torques or positions. Depending on the control mode, the low-level controllers guarantee that the motor drive will receive the desired torque or position values, respectively. For this cascaded control structure to be effective, the low-level controllers have to operate at a control frequency higher than the control frequency of the high-level control. For example, typical values are 1 kHz for the control-software layer and 3 kHz for the low-level controller.

3.1.3. Control system

The control-software layer, namely the MAR Control on-board presented in Fig. 10, will generate control commands for the MAR system to perform the required operation tasks (e.g. walking, transportation and repositioning). In particular, impedance controller for space manipulators are effective in dealing with contacts while performing on-orbit tasks [6]-[7]. The impedance controller provides joint torques commands and it ensures stable behavior during the contact. Hence, due to its suitability, the impedance controller is implemented for the control of the MAR system, which is required to perform contact-oriented tasks.
A unique aspect of the MAR is its modular design, which requires operations in different morphologies. However, this requires the handling of multi-contacts for preforming several operations defined in the project. A key aspect in these operations is that the MAR system is required to latch with one or more SIs. This introduces the crucial problem of stabilizing the transient contact phase, which precedes the latching completion. In [8], a unified controller has been designed for a reconfigurable robotic system composed of a torso and independent arms, e.g. the MAR system. The designed impedance controller ensures passivity during external contacts (e.g. latching with the SIs), which provides a measure of stability against perturbations. The SI latching points of the MAR system are modeled as bilateral constraints, and the number of constraints are given by the number of latching points. These constraints are applied in the equation of motion of the MAR mechanical plant, which is written as,

$$M(q)\begin{bmatrix}\dot{V}_b\\ \ddot{q}\end{bmatrix} + C(q,\dot{q},V_b)\begin{bmatrix}V_b\\ \dot{q}\end{bmatrix} - \Phi^T\lambda = \begin{bmatrix}0\\ \tau\end{bmatrix}, \qquad (1)$$

where V_b is the body velocity corresponding to the pose g_b, $\dot{q}$ is the joint velocity, M and C are the matrices of inertia and Coriolis/centrifugal terms, Φ is the constraint Jacobian due to the holonomic constraint (SI latches) and λ is the vector of Lagrangian multipliers. On the right-hand side, the actuation is only through the joints's actuation τ. Note that the MAR plant is a redundant kinematic chain. In other words, it possesses more degrees of freedom than the Cartesian task it intends to accomplish. In particular, during the Cartesian task, the redundancy enables a motion in the so-called null space of the robot, although the end-effector will achieve the Cartesian task (see [9] for details about null space). Therefore, for having stable operation, the controller will be augmented with an extra torque component, which will act in the null space without interfering with the primary Cartesian task of the impedance control. More formally, the overall Cartesian impedance control law is given as:

$$\hat{\tau} = \tau_{ff}({g^*}_d) + \tau_n(q) + \tau_{fb} + \tau_{jl}(q), \qquad (2)$$

where τ_{ff} are the feed-forward terms for the trajectory tracking of the desired pose, ${g^*}_d$, τ_n is the null-space control torque and τ_{fb} is the feedback part, which is written as,

$$\tau_{fb} = T(q)^T\left(-\gamma - DT(q)\begin{bmatrix}V_b\\ \dot{q}\end{bmatrix}\right). \qquad (3)$$

D is a positive-definite matrix of the damping gains, $T(q)$ is the Jacobian and γ consists of the total wrench(es) due to the proportional action corresponding to the potential φ, which provides the P-control (proportional) term.

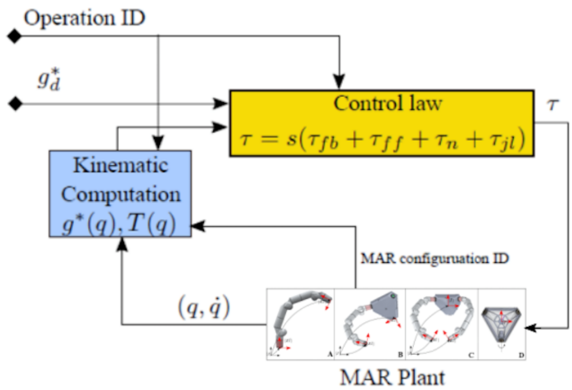

Figure 11. Block Diagram of the MAR system.

For safety in the operation, a torque component, τ_{jl}, is added in the control. This prevents the violation of the hardware limit of the joints of the MAR system and this is designed using a repulsive spring-damper behaviour. The convergence of the control law can be shown using

Lyapunov stability analysis as demonstrated in [8].

A block diagram of the proposed control-software layer is shown in Fig. 11, where the Cartesian control law is shown in the yellow block. The required kinematic computations are performed in the blue box while using the MAR plant joint measurements. The plant can be the one of the 1-arm, 1-arm + torso, 2-arm or torso system.

3.2. TESTBED

3.2.1. Dummy spacecraft

The dummy spacecraft, illustrated in Fig. 12, is composed of:

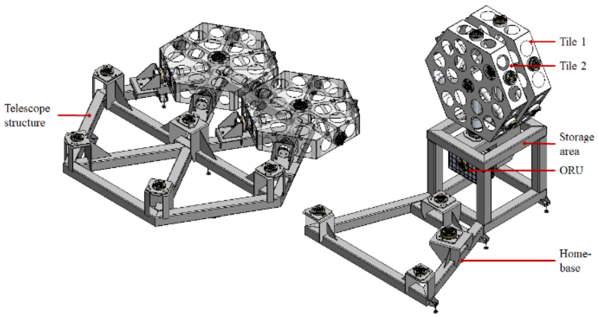

Figure 12. Overview of the MIRROR dummy spacecraft.

- A home base (see Fig 13): this is a platform for hosting the robot, allowing the robot to access the payloads and the telescope structure. The home base is equipped with an ORU compartment for hosting electronic devices (for example). Four HOTDOCKs are mounted on the home base. Three HOTDOCKs (one passive and two mechanical) are used for mating with the MAR HOTDOCKs. The fourth one (passive) is dedicated to the ORU attachment;

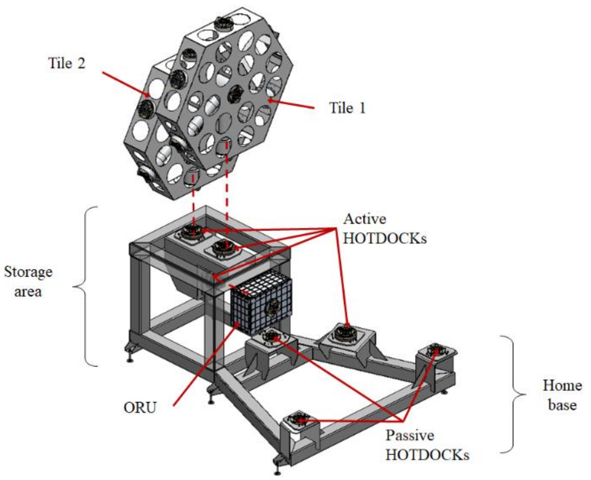

Figure 13. Detailed design of the home base and storage area.

- A storage module (see Fig. 13): this is the structure linked to the home-base on which the payloads (mirror tiles and ORU) are initially mounted. Three HOTDOCKs (mechanical) equip the storage module for attaching which are used to attach payloads (mobile mirror tiles and ORU);
- A telescope structure (see Fig. 14): this is a fixed structure involving prepositioned tiles. This structure is linked to the home base. Nine HOTDOCKs equip the telescope structure. Five (four mechanical and one passive) are located on the back surfaces of the prepositioned tiles. This configuration will permit to show walking scenarios without being connected all the time to the spacecraft. Four HOTDOCKs (all passive) are on the side surfaces of some prepositioned tiles. Their location have been chosen to show tile assemblies involving two and three HOTDOCK attachments simultaneously.

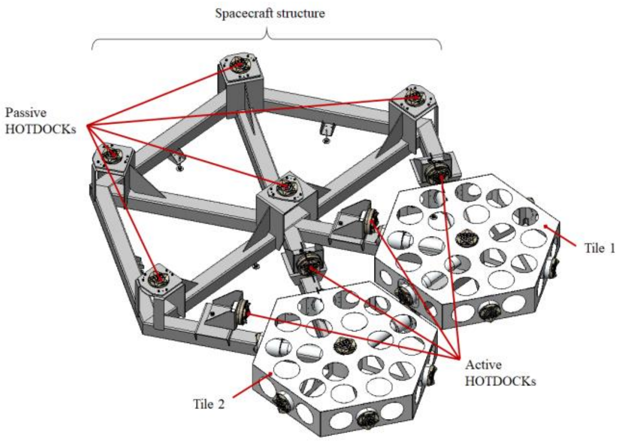

Figure 14. Detailed design of the telescope structure.

3.2.2. Payloads

The dummy payloads are as follows:

- Two hexagonal mirror tiles of 10kg and 1.2m large (corner to corner) as shown in Fig. 15. Each tile is equipped with a passive SI on the back surface and features the following SI configuration on the side surfaces:
  - The first tile has three passive SIs and three dummy ones;
  - The second tile has two passive SIs, an active one and three dummy one.
- The ORU is a parallelepiped aluminium structure equipped with two passive SIs as shown in Fig. 16, whose weight is 5kg and size is 275x390x190mm.

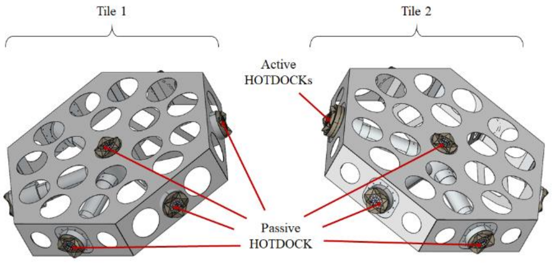

Figure 15. Detailed design of the mobile tiles.

Figure 16: Detailed design of the ORU.

3.2.3. Weight compensation device

To support the MIRROR breadboard on earth, the use of a weight compensation device is needed. Since the MIRROR breadboard involves a multi-arm robotic manipulator and mobile payloads, a passive gantry crane mechanism with a passive rolling bridge equipped with trolleys to support the system along the X and Y directions was selected (see Fig. 17). The Z axis load is supported by a cable system involving pulleys and counterweights.

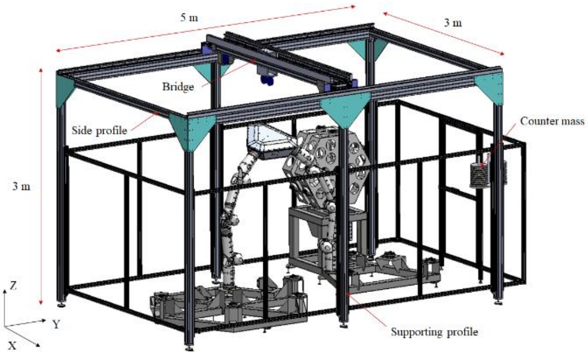

Figure 17. Gantry crane system with testbed.

The gantry crane structure is adapted to allow the MAR to reach all positions of the testbed. The structure is composed of aluminium profiles. It is fixed to the ground by six profiles with specific interfaces allowing the levelling of the structure.

The gantry crane design was driven by the objective of ensuring minimal deflection and stress. It is primordial to limit all possible interferences of the structure on the movement of the MAR. The weight compensation device is passive and needs to have almost no impact on the motions and trajectories of the MAR. To do so, the stiffness and the guiding were the main drivers for the structure design and component selection.

To ensure that the MAR can move freely all around the workspace, the bridge can translate in one direction and the platform connected above the MAR can translate along the bridge itself, as shown in Fig. 18.

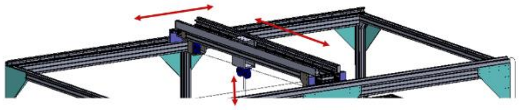

Figure 18. Possible motions of the offloaded object.

The bridge is composed of two identical profiles and the MAR is connected to the translating platform on the bridge.

The gantry crane system is the mechanical structure of the weight compensation device. The compensation itself is done by a counter mass system, as depicted in Fig. 19. A mass is attached to a cable connected to the torso of the MAR and fixed to the structure at the opposite end of the structure from the counter mass. The cable is directed thanks to multiple pulleys.

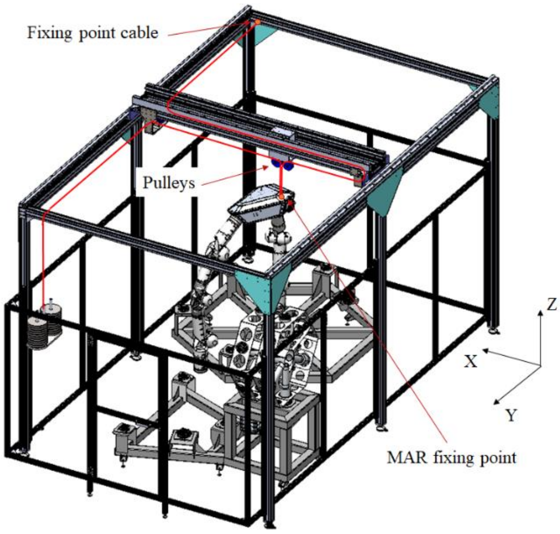

Figure 19. Cable routing along the gantry crane.

Having the cable in this configuration allows the motion in X and Y directions to have no impact on the counter mass. Only the translation of the MAR in the Z direction as an impact on the counter mass. Thus, the counter mass does not interfere with the movement on the XY plan and compensate equally in all positions.

4. GROUND SEGMENT

The ground segment is composed of:

- The programming and control station to allow monitoring and controlling the demo setup. It will run on a standard computer (x86), with Linux OS (Ubuntu 18.04 or above), running the Console/Service.
- The EGSE that provides the electrical components required to operate the system. The EGSE is composed of:
    - a power supply 2 channels: the first one dedicated to power the robot, the second

one dedicated to power the testbed devices.
    - A cPDU.
- The testbed network featuring:
    - A CAN network for controlling the testbed Interconnects.
    - A CAN network for communicating high level commands to the MAR.
    - A wireless router for remote connection with the different MAR OBC.

5. CONCLUSIONS & PERSPECTIVES

This paper describes the ground demonstrator design for a multi-arm robot dedicated to on-orbit large assembly, performed in the scope of the ESA TRP MIRROR project.

This technological ground breadboard, derived from the MIRROR mission concept of operations, aims to demonstrate the entire scope of operations of this novel modular installation robot in a representative environment.

Future work will focus on performing the hardware and software integration of the breadboard as well as testing the MAR within the MIRROR demonstrator. In parallel to this activity, the use of such modular robotic systems is assessed in the scope of in-orbit very large structure assembly applied to space solar power plant through the ESA OSIP SKYBEAM study.

6. ACKNOWLEDGEMENTS

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