MIRROR – A Modular and Relocatable Multi-arm Robot Demonstrator for On-orbit Large Telescope Assembly

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ABSTRACT

The ESA MIRROR project deals with a modular multi-arm installation robot to address the challenge of in space assembly of modular structures. 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 equipment.

1. INTRODUCTION

Large structures in space are an essential and recurring element for space exploitation and exploration. Future outposts, solar facilities, and telescope sizes will be major drivers for new space technologies [1]. While self-deploying structures contained in typical launcher fairings are approaching their limits because of the growing size of foreseen structures, large structures divided into modules and further assembled in space will become the preferred implementation approach [2]. In-space assembly of large structure is extremely challenging, but technologies like standard interconnects and dexterous orbital robotics open new opportunities for such applications [1-3].

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

In the project, the large spacecraft structure, modules and installation robot are assumed to be equipped with HOTDOCK Standard Interconnects that enable mechanical, data, and power transfer [4]. Modules can mate with each other, robotic manipulators can capture, transport and install them, and the installation robot can relocate over the spacecraft structure and modules.

Figure 1. Artist representation of the MAR concept.

This work leverages results, concepts or ideas from a number of previous European projects: H2020 Space Robotics projects (ESROCOS [5], SIROM [6], PULSAR [7] and MOSAR [8, 9]), ESA ISS EUROBOT project [10], ESA TRP Dexterous Robot Arm (DEXARM) [11] and standard interconnects [4].

The structure of this paper is as follows: Sec. 2 recalls MIRROR's concept of operations and Sec. 3 follows with the design driver and analysis. Sec. 4 presents the breadboard demonstrator overview, while Sec. 5 depicts the multi-arm robot and Sec. 6 its testbed. Sec. 7 finally provides a conclusion on the work achieved and presents perspectives on future activities.

2. ROBOT CONCEPT OF OPERATIONS

MIRROR is a robotic system which provides self-assembly and self-maintenance capabilities to a satellite. In this scenario, a hosting spacecraft located in the Sun-Earth Lagrangian point is assumed, acting also as a logistic node for additional servicing operations. As a baseline, the hypothesis is to have a multi arm robot stowed in the satellite at his home base attached to the satellite primary structure by means of standard interconnects [4]. The spacecraft includes a service module, a payload module and a dispenser storing the individual mirror tiles. The multi arm robot is in a stowed configuration during the launch phase.

Once the spacecraft has reached the Sun-Earth L2 point, the assembly sequence is initiated. The operation is assumed to start with the deployment of a heat shield to protect the temperature-sensitive electronics of the telescope imager. The mission is completed when all the hexagonal mirror tiles (1.2m side to side) are installed in order to reach the primary mirror final aspect. A detailed sequence of assembly for such large telescope structure featuring such a robotic system can be found in [12].

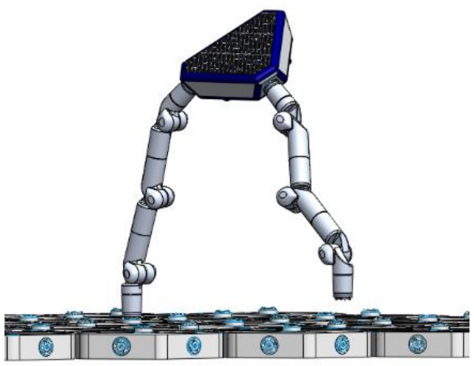

Figure 2. Artist representation of the walking operation.

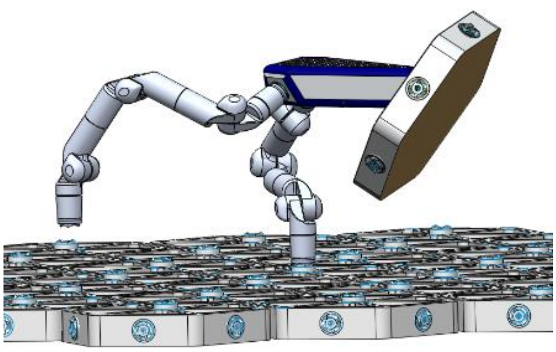

Figure 3. Artist representation of the transportation operation.

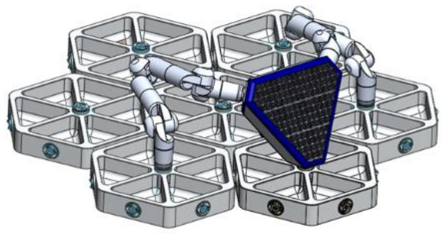

Figure 4. Artist representation of the manipulation operation.

To perform the assembly of such structure, the primary operations considered for the multi-arm installation robot are (1) re-localization to a new attachment point on the satellite, (2) transportation and (3) manipulation of hexagonal mirror tiles or ORU using its arm's or torso's SIs (Figs. 2, 3 and 4). Additional MAR operations, inherent to the modular concept of this robot, are extensively detailed in [12].

3. DRIVERS & ANALYSES

Since the MIRROR project adopts a modular approach to the mission using SIs, the proposed robotic device will adopt the same philosophy. Modularity should reduce the overall complexity by splitting a monolithic system into less complex subsystems, namely torso and arms. This approach should also bring a longer lifetime to the device (maintenance-free design, built-in growth potential and upgradeability, replaceable modules for maintenance) and should reduce risks related to long planning and development phases (technology obsolescence) [13].

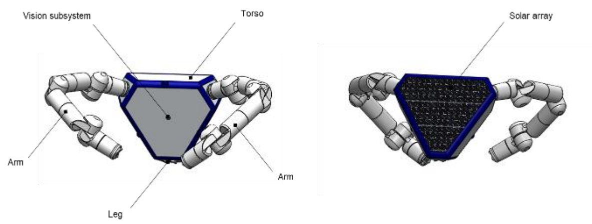

Figure 5: Multi-arm robot overview

The different modules are independent entities that can be gathered by the mean of SIs to form the MAR as shown in the figure below.

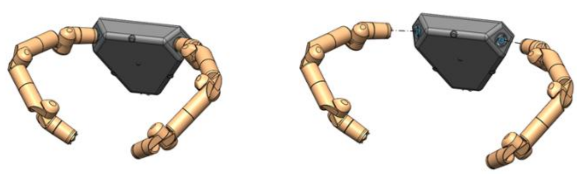

Figure 6: MAR robotics subsystem assembly

The choice of 7-DoF robotic manipulator coupled with the human like arm with non-spherical wrist configuration gives the manipulator a symmetry that strengthens its modularity. Indeed, the 7-DoF arm has, by design, the capability to be mounted at either extremity without modifying the structure of the overall robotic system.

A 1-DOF leg (revolute joint) has been chosen to allow the torso to spin around when it is directly attached to the spacecraft. If the leg is holding a payload, this DOF can be used as a redundant motion for positioning purposes.

The kinematics of the MAR was selected in order to guarantee the completion of the mission whatever the configuration of the robot. Thus, the MAR is able to perform the operations even if one of its robotic subsystem is missing. Fig. 7 illustrates as an example the 2D reachability and dexterity maps of the MAR wrt the telescope structure in these different configurations when performing a walking operation.

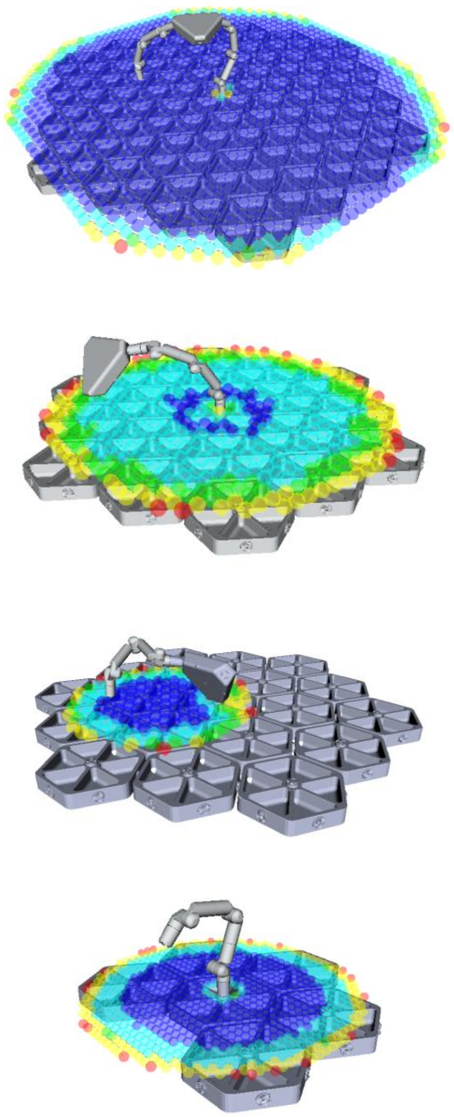

Figure 7: 2D reachability and dexterity maps of the MAR wrt the telescope structure in its different configurations when performing the walking operation. from top to bottom: Torso+2arms, Torso+1arm, standalone arm.

4. DEMONSTRATOR OVERVIEW

Developed at TRL4, the MIRROR technological demonstrator [14], illustrated in Fig. 8, 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.

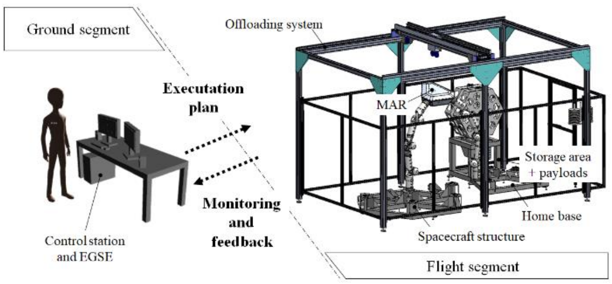

Figure 8. MIRROR's ground demonstrator concept.

5. MULTI-ARM ROBOT SYSTEM

5.1. Hardware

The MAR design makes use of HOTDOCK standard interconnects (see Fig. 9) to gather the robotic submodules (arms and torso) and interact with payloads (mirror tiles and ORU). Two interconnects are located at each extremity of each robotic arm and three interconnects features the torso. Two of them are fixed and one, called leg, is able to rotate. The HOTDOCK interconnects guaranty the mechanical connections and load transfer between the robotic entities and payloads. HOTDOCK allows also for power (48V) and data (CAN and EtherCAT) transfers. More details about HOTDOCK can be found in [4].

Figure 9: HOTDOCK Standard Interconnect

Nine large duty and six small duty hollow shaft joints (see Fig. 10) make the MAR moving. Each robotic arm is composed of four large and three small joints. The torso leg, illustrated in Fig. 11, features a large one. This dedicated family of joint is based on the following core components: Frameless BLDC motor, Harmonic Drive Gears, Preloaded cross roller bearings and deep groove ball bearings, magnetic incremental and absolute encoder, Torque sensor and electromagnetic brake.

Figure 10: Arm's robotic joints.

Figure 11: Torso's leg.

The joints and HOTDOCK interconnects are linked with each other with aluminium structural elements. The robotic arm structures are composed of seven joints and eight limbs (see Fig. 12) arranged in a symmetric $R \perp R \perp R \perp R \perp R \perp R \perp R$ configuration, where R indicates a revolute joint and $\perp$ the orthogonality between two successive joint axes. Dimensions of the arms are detailed in Fig. 13. Each arm has a mass of about 40kg.

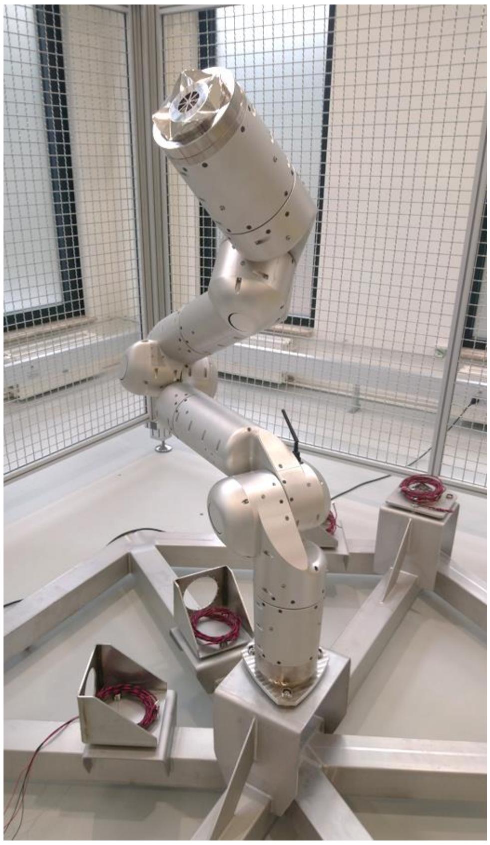

Figure 12: MAR's arm.

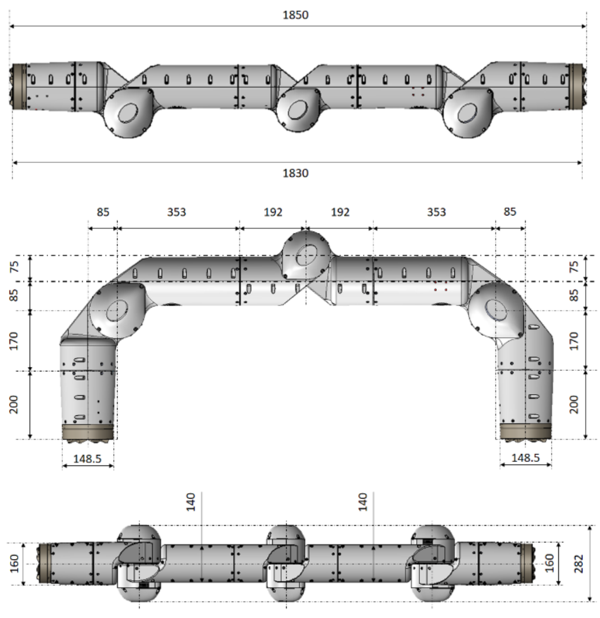

Figure 13: Manipulator dimensions.

The torso, illustrated in Fig. 14, is a truncated tetrahedron structure with an equilateral triangle baseline, composed of internal and external aluminium panels. The structure of the torso offers a series of attachment points for hooks allowing its connection with the weight compensation device. Dimensions of the torso are detailed in Fig. 15. The torso has a mass of about 28kg.

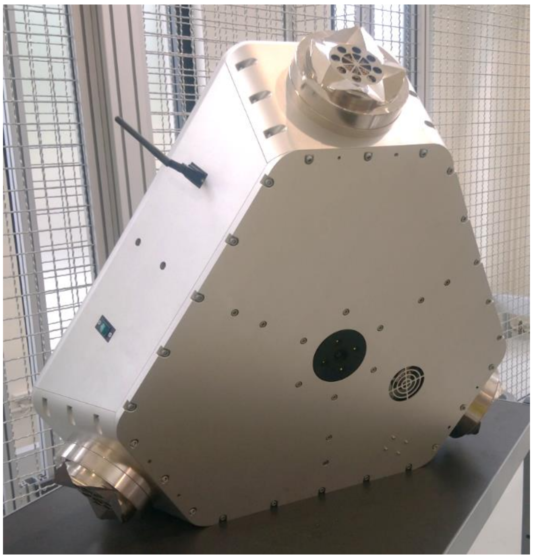

Figure 14: MAR's torso.

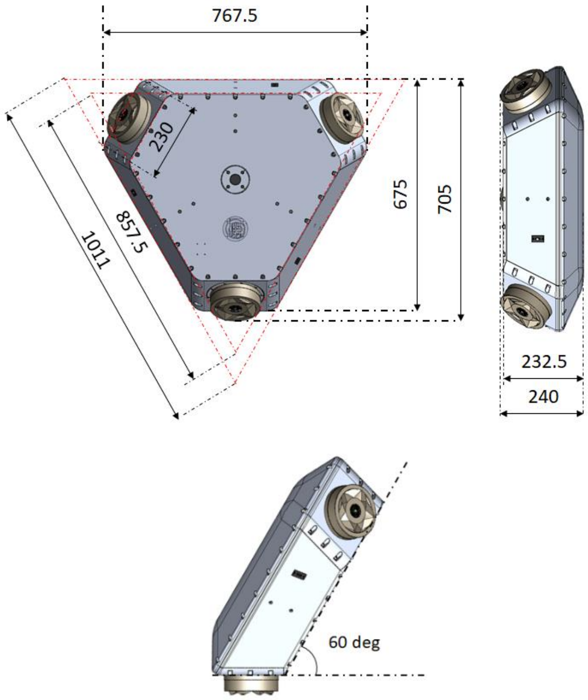

Figure 15: Torso dimensions.

Each robotic arm as well as the torso embed a computer as central component. Each computer manages the internal control of its respective robotic module. These computer are Intel NUC boards running Ubuntu. This solution, equivalent to the MCC computer, offers the required compactness while providing a standard platform to integrate the different software applications.

Each on-board computer interfaces three data:

- CAN and WIFI buses for “high level” non-deterministic telemetry and telecommand (TM/TC) communication with the MCC.
- CAN bus for local control of the HOTDOCK interfaces.
- EtherCAT bus for low-level deterministic communication with the joint drivers and connected robotic modules.

Each joint is equipped with a local controller for the closed loop position/current control of the actuator and the measurements of the joint sensors. All joint controllers are interfaced through the EtherCAT bus, managed by the on-board computer, which ensures real-time exchange of information required for the control algorithm of the arm. When connected to the torso, the arm’s on-board computers are monitored by the torso’s one through the EtherCAT bus.

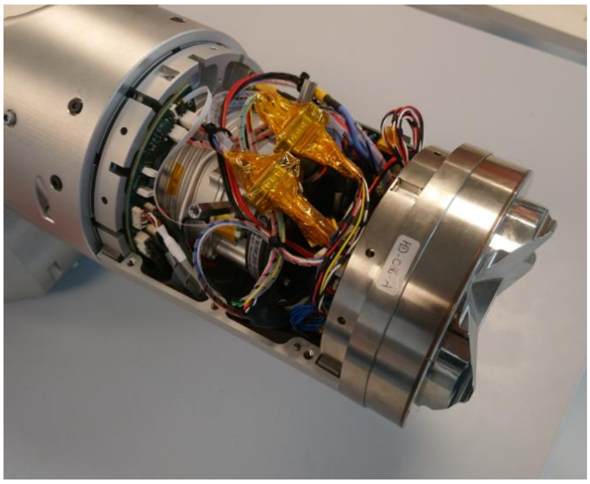

Figure 16: Arm’s wrist avionics layout

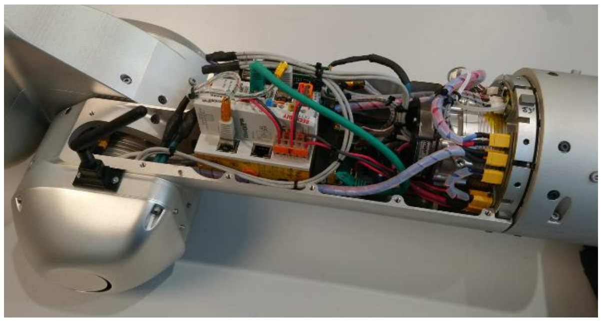

Figure 17: Arm’s central avionics layout: OBC, EtherCAT/CAN/WIFI communication modules, PCU

The MAR is powered by the tesbed’s 48V power bus, through the power interface connector of HOTDOCK. The 48V bus is directly interfaced with the joint drivers that will manage the power interfaces to the motors and sensors of the joints. Local DC/DC convertors provide the required 24V to power the HOTDOCKs and 19V for the on-board computer. Each robotic module is also able to control its power transfer, passing through the HOTDOCKs interfaces, thanks to power relays.

The MAR’s torso additionally features a battery subsystem and a vision subsystem:

- The battery is charged during nominal operation through the main 48V bus and switch automatically to “supply mode” in case of a power failure.
- The vision subsystem located at the center of its “belly” panel, depicted in Fig. 19, includes a camera and LEDs.

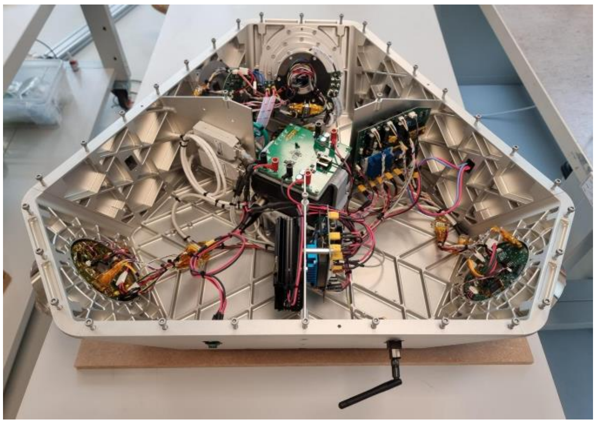

Figure 18: Torso’s avionics layout.

Figure 19: Torso’s vision subsystem: lighting module off (left) / on (right).

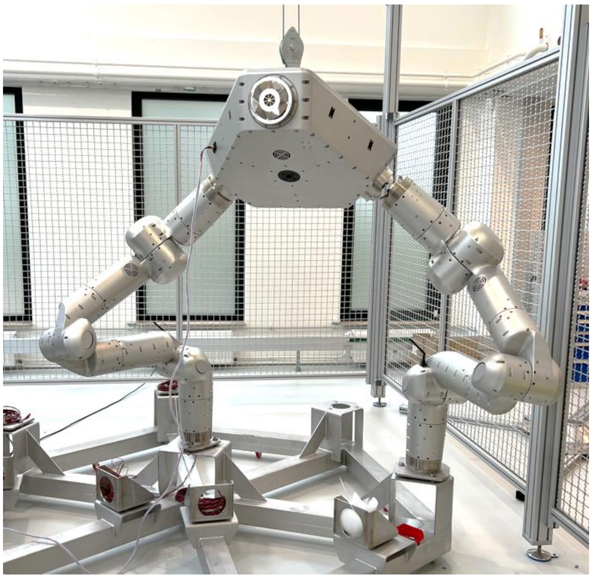

Figure 20: Multi-Arm Robot while right arm attachment operation.

As introduced in Sec. 3, the prior mentioned robotic modules, namely arms and torso, are compatible and can be connected thanks to the HOTDOCK standard interconnects to form the MAR, as illustrated in Fig. 20 and 21. Its total mass is about 108kg. The idle power consumption of the MAR is about 200W while its peak consumption is assessed at 850W (all 15 joints under maximum torque).

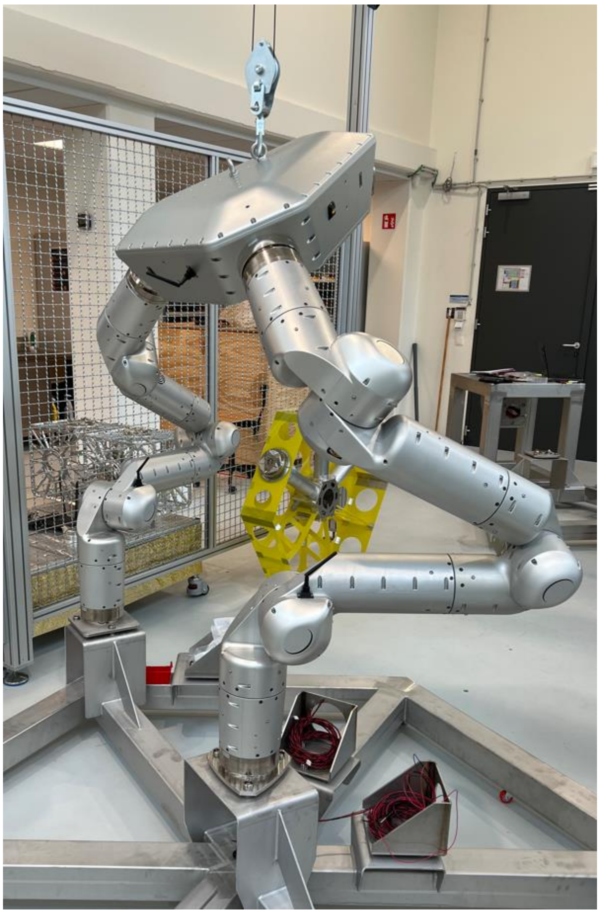

Figure 21: Multi-Arm Robot demonstrator.

5.2. Software & Control

The Multi Arm Robot 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.

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.

The control-software layer generates 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 [15]-[16]. 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 [17], 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 modelled as bilateral constraints, and the number of constraints are given by the number of latching points.

Note that the MAR 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 [18] 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.

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 [17].

A block diagram of the proposed control-software layer is shown in Fig. 22, 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 system joint measurements. The configuration can be the one of the 1-arm, 1-arm + torso, 2-arm or torso system.

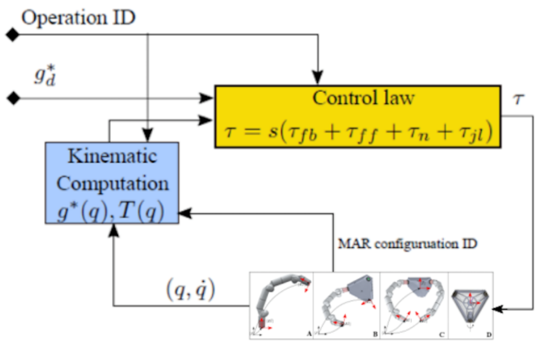

Figure 22. Block Diagram of the MAR system.

6. TESTBED

6.1. Dummy spacecraft

The dummy spacecraft (see Fig. 23) is composed of a home base, storage area and a telescope structure. The home is a platform that hosts the robot when not used and provides an excess to the payloads and to the telescope structure. The home base is equipped with an ORU compartment for hosting electronic devices (for example). The storage area is a structure on which the payloads are initially mounted. The telescope structure is a fixed structure involving prepositioned dummy tiles, allowing the robot to move along it. The different structures of the dummy spacecraft feature SIs. The location and type of SIs have been chosen to reduce the complexity of the testbed and to provide a relevant workspace to the robot in order to illustrate and perform its scope of operations.

6.2. Weight compensation device

The weight compensation device of MIRROR is a passive gantry crane mechanism with a passive rolling bridge equipped with trolleys to support the system along the X and Y directions (see Figs. 24 & 25). The Z-axis load vector is supported by a cable system involving pulleys and counterweights. This configuration allows for moving in X and Y directions without inducing a Z motion. Thus, only a translation of the MAR in the Z direction influences the height of the counter mass. This structure is composed of aluminum profiles and measures 3mx5mx3m.

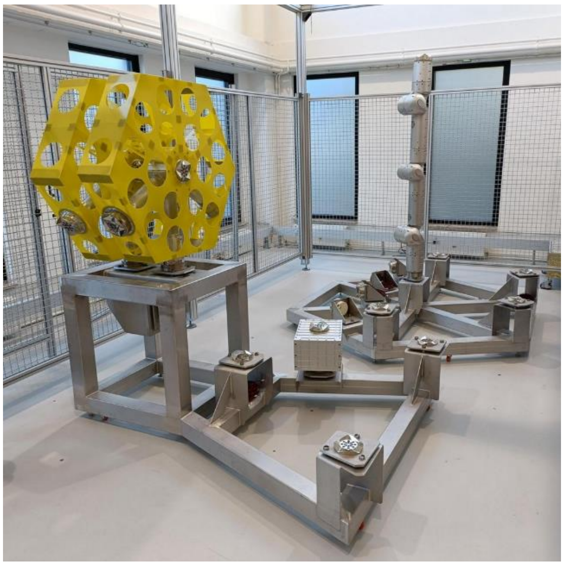

Figure 23. Overview of the MIRROR dummy spacecraft.

Figure 24. MIRROR's weight compensation device.

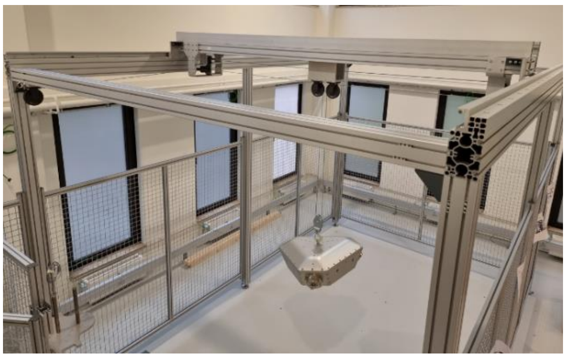

Figure 25: Offloaded MAR's torso.

6.3. Payloads

The dummy payloads are composed of two hexagonal mirror tiles and one parallelepiped ORU. Each payload features SIs as illustrated in Figs. 26 and 27. The mirror tiles are 1.2m large (corner to corner) and weigh 10kg. The ORU features a 275x390x190mm aluminum structure and weighs 5kg.

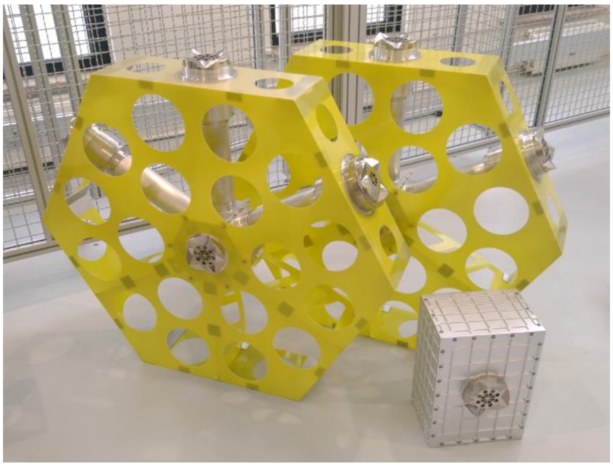

Figure 26: MIRROR's payloads.

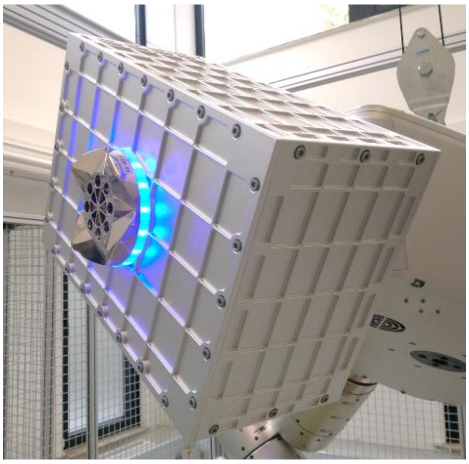

Figure 27: MIRROR's ORU connected to the MAR's leg.

6.4. MCC and EGSE

The ground segment of this testbed is composed of a programming and control station and an EGSE. The programming and control station monitors and controls 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 provides the electrical and data components required to operate the system. It mainly involves a power supply with two channels (one dedicated to power the robot, the second one dedicated to power the testbed devices), a CPDU, two CAN networks (for controlling the testbed interconnects and for communicating high-level commands to the MAR) and a wireless router for remote connection with the MAR OBC.

7. CONCLUSIONS & PERSPECTIVES

This paper describes the ground demonstrator (TRL4) 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 achieving the test campaign of the MAR breadboard 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 [19] and to orbital logistics platform for ISAM.

8. ACKNOLEDGEMENT

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