RE-LOCATABLE MANIPULATOR FOR ON-ORBIT ASSEMBLY AND SERVICING

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ABSTRACT

This paper focuses on the design and initial breadboard testing of MIRROR, a robotic system for on-orbit structure assembly and spacecraft servicing.

The proposed flight system consists of three identical 6-DOF robotic arms and a central torso. The standard interconnect devices installed as end effectors (SIROM) allow this robotic system to manipulate the structures to be assembled and also to move across the already assembled part of the structure. The on-board control system allows executing autonomously all the operations needed for the complete assembly of the structure, including precise manipulation based on vision. The breadboard system, currently being integrated, is undergoing subsystem test that indicate that the required accuracy can be achieved. This breadboard is expected to demonstrate in laboratory conditions the feasibility of the overall approach.

1 INTRODUCTION

On-orbit servicing and on-orbit assembly are expected to have a significant and growing impact in the space industry in the next years. In particular, the deployment of large structures in orbit is expected to be an essential and recurring operation for future space exploitation and exploration. For instance, the capability to assemble large structures in orbit would allow deploying arbitrarily large telescope mirrors and radar/communication reflectors, which parts could be disposed by one or several launchers. The capability to provide in-orbit servicing could increase lifespan, performance or even change the mission objective of a space system, through the use of modular spacecraft designs.

The Multi-arm Installation Robot for Readying ORUS and Reflectors (MIRROR) is an ESA-funded activity focusing on the design and breadboarding of a robotic system for on-orbit operations, particularly on-orbit large structure assembly and spacecraft servicing for maintenance, repairs or upgrades. The MIRROR activity shall specifically produce:

- The preliminary design of the robotic flight system
- A breadboard of the robotic system (TRL4)
- The testbed needed to test the breadboard.

MIRROR is expected to develop and demonstrate the technologies needed for making possible such assembly/servicing missions, namely:

- The development of a mobile manipulator, able to re-locate itself across a spacecraft or across the structure that it is assembling, eventually transporting the structural parts to be assembled or the Orbital Replacement Units (ORUs) to be deployed.
- The evolution/upgrade of the standard interconnect devices needed for mechanical coupling and data, power and fluidic interchange, between the manipulator and the structure/spacecraft and between the assembled parts.
- The evaluation of vision and control techniques allowing the precise positioning and manipulation needed for the assembly/reconfiguration tasks.
- The assessment of the autonomy level needed to perform the complex sequences of operations needed to complete an assembly/reconfiguration process.

Several robotic systems have been proposed in the past to accomplish assembly and servicing operations [1][2]. Among the proposed systems, PULSAR [3], oriented to telescope reflector structure assembly, and MOSAR [4], focused on spacecraft reconfiguration and servicing, have been partially demonstrated in laboratory tests. However, it is still to be demonstrated that an arbitrarily large structure can be assembled with the required tolerances and with the needed autonomy by a mobile manipulator able to transport the structure parts or the orbital replacement units (ORUs).

Currently, the preliminary design of the MIRROR flight system and the detailed design of the MIRROR breadboard and testbed systems have been completed.

The manufacturing and integration of the breadboard and testbed is near completion, and the first subsystem tests have been already conducted.

This paper focuses on the design, and validation of the MIRROR breadboard, and presents the first results obtained during subsystem testing.

2 REFERENCE MISSION SCENARIO AND CONCEPT OF OPERATION

The reference mission scenario consists of the assembly of a multi-ring telescope reflector composed of hexagonal Single Mirror Tiles (SMTs). The SMTs are 1.2 m wide and are equipped with Standard Interconnects (SIs) that allow assembling them to each other, and also permit the MIRROR robot to grasp and manipulate them. The MIRROR relocatable manipulator can grasp and manipulate the SMTs to be assembled, while it can also move itself (walk) across a structure, using its three limbs, which are equipped as well with standard interconnects (SI) as end-effectors. Note that MIRROR can use indistinctly two of its limbs to walk across the reflector structure it is assembling or across the spacecraft, while transporting a SMT to the point where it has to be assembled. The SIs provide mechanical coupling, power and data interfaces between the manipulator and the SMTs, between assembled SMTs, and finally between the SMTs and the spacecraft main body. Fig. 1. and Fig. 2 illustrate the Manipulator Attach and SMT Assembly operations, while Fig. 3 shows the sequence of main operations for the assembly of the telescope reflector.

A similar reference mission focuses on the reconfiguration of a modular serviced spacecraft through the installation/replacement of modular Orbital Replacement Units (ORUs) also equipped with SIs.

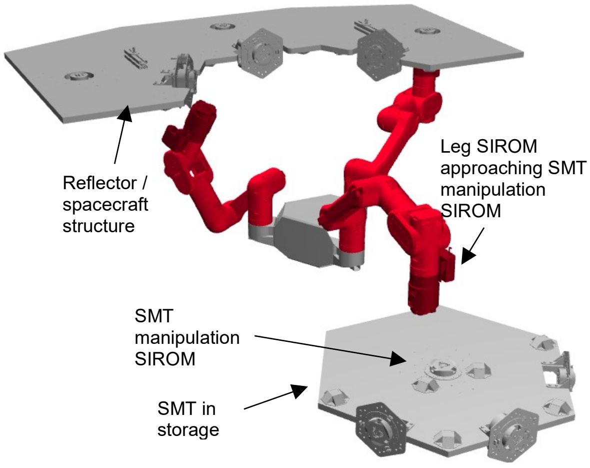

Figure 1. Manipulator Attachment operation.

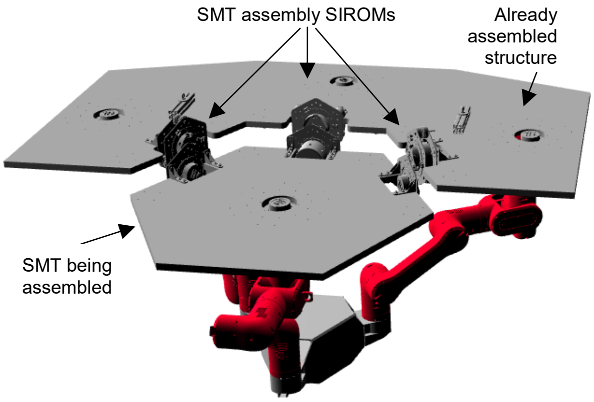

Figure 2. SMT Assembly operation.

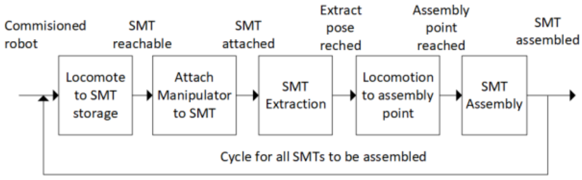

Figure 3. Sequence of operations for a telescope reflector assembly mission.

3 BREADBOARD SYSTEM

3.1 Relocatable manipulator

The Multi Arm Relocatable Manipulator (MARM) consists of three identical robotic arms and a central torso to which the arms are connected. The kinematics of the arm was derived through a number of studies considering manipulability and workspace optimization. Each arm has 6 joints, which implement a 2 DOF shoulder/hip arrangement, an elbow/knee joint and a 3 DOF wrist / ankle complex terminated to a SIROM end-effector interface. The corresponding DH parameters of this preliminary kinematics are reported in Fig. 4.

DH Frames:

j	q	d [m]	a [m]	α [rad]
1	q_1	0	0	-π/2
2	q_2	0	0.4	0
3	q_3	0	0	π/2
4	q_4	0.403	0	-π/2
5	q_5	0	0	π/2
6	q_6	0.337	0	0

$q_0 = [\,0\ -\pi/2\ \ \pi/2\ \ 2\ 0\ 0\ 0\,]$

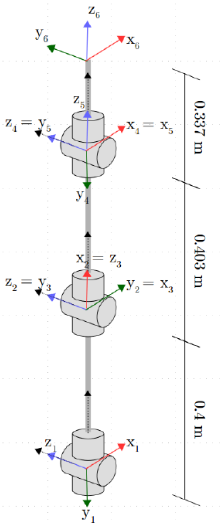

Figure 4. DH parameters of the MARM.

The primary component for realizing the MIRROR limb kinematics is the actuation unit that is used to power the joints of the robotic system. Based on the simulation studies performed during the preliminary design phase, two actuator sizes were identified based on the torques requirements results obtained from these simulations.

The actuaton unit is implemented using the foundation actuation technology of [5,6] and consists of a DC brushless motor combined with a harmonic drive reduction unit. Motor, gear and joint sensing have been highly integrated to optimize the weight and dimensions of the joint. The sensing system of actuator includes two position sensors, one torque sensor and two temperature sensors. One encoder monitors the position of the motor side shaft wihle another encoder measures the position of the output link side shaft pulley (harmonic drive output). A torque sensor is based on a custom load cell structure that was sized appropriately for the two sizes of te actuator to measure the torque generated at the output.

The module includes also a brake module and local electronics (Servo Control Unit SCU) is included into each robot joint. Finally th actuator incorporates two temperature sensors, which are installed to monitor the motor windings and SCU electronics temperatures. The harness cabling exploits the hollow shaft architecture. In Fig. 5 the main specifications of the two sizes of the actuator are displayed while Fig. 6 presents the physical prototpyes of the actuators. In the cross section is shown.

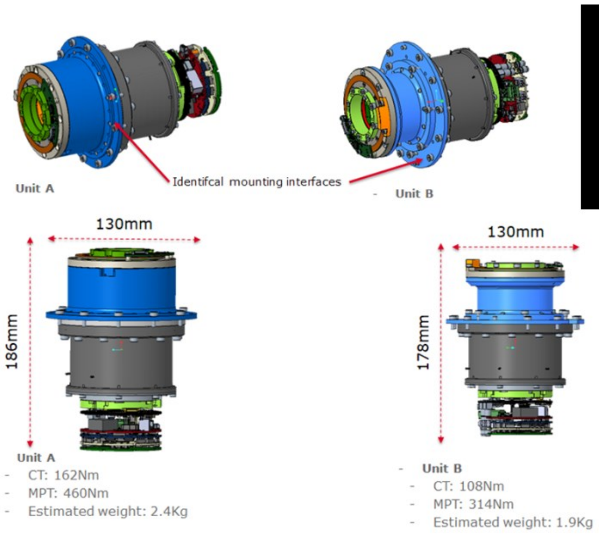

Figure 5. Actuation module sizes“A” and “B” with their main specifications in terms of size, weight and torque capacity.

The SCU of the actuation was designed following a stack topology permitting to be fully integrated close to the motor assembly, which significantly reduces the complexity of the wiring along the manipulator arm requiring only the routing of the power and communication cables through the hollow shaft of the actuators and along the arm. . Each layer incorporates different functions, accommodating the logic circuits, the EtherCAT communication interface, the power management and the power inverter on the top layer to facilitate heat dissipation.

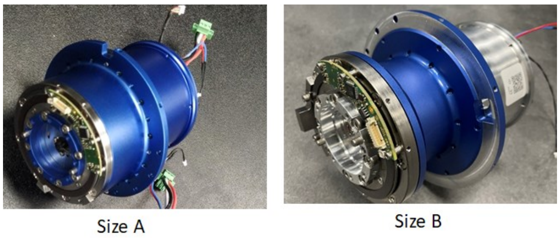
Size A
Size B

Figure 6. Prototypes of the MARM actuation units.

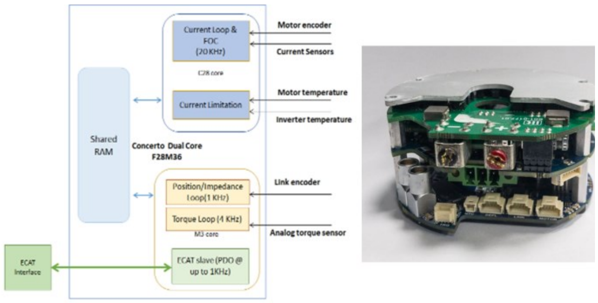

Figure 7. Servo Control Unit

To implement the kinematics of MARM two types of structural cell modules were realized, each of them housing two actuation units forming a 2-DOF modular sub-body. A L-Shape module incorporating two actuators of size A is used to implement the shoulder complex while another L-Shape module that integrates one size A and one size B unit is used in the elbow segment. Finally, a T-Shape module consisting of two size B actuators implements the wrist complex. An overview of the single arm design as well as the realized single arm prototype are presented in Fig. 8.

The overall MARM system integrates three identical robotic arms mounted in a modular manner on the three sides of a hexagonal shape central pelvis structure. Apart from forming the mechanical link among the three arms, this pelvis structure also forms the compartment of the robot control units, communication devices, power management electronics and battery unit with its associated charging system.

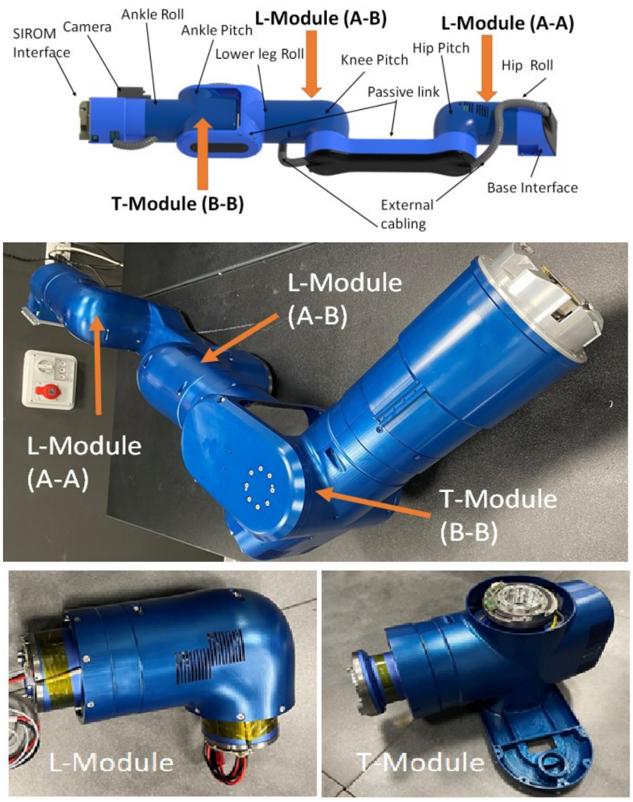

Figure 8. Single MARM limb showing the use of the 2-DOF L-Shape and T-Shape modules.

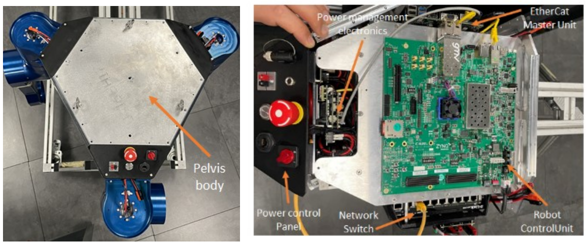

Figure 9. MARM pelvis body showing the mounting location of the three arms and the arrangement of the electronics and robot control units.

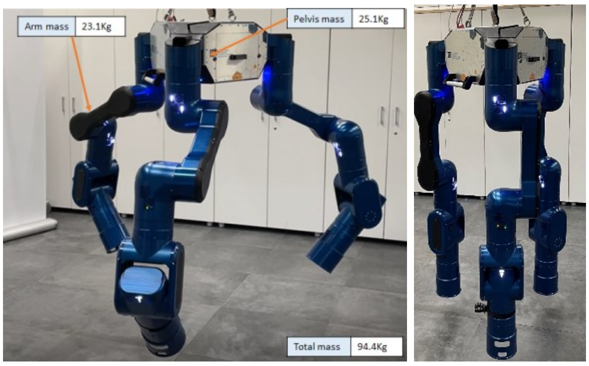

Figure 9. Complete MARM prototype.

3.2 Control system

The onboard Robot Control System allows executing autonomously all the operations needed for the complete assembly of the structure. On-board Control Procedures (OBCPs) are used to encode the complex sequence of nominal operations. These OBCPs, written in micro Python language include conditional branches, which allows encoding checks to verify that each operation step is executed successfully. In case an operation fails a reattempt can be automatically launched (e.g. reattempt of an assembly).

Different motion modes have been implemented to meet the needs of the different stages of a typical assembly/disassembly operation. In particular, the following motion modes are considered.

- Free motion: When a manipulator must reach a point and there is no/little risk to impact against any object in its surroundings, the arm moves with a simple joint position control. The trajectory is pre-computed with an RRT* path planner to ensure there is no collision against known objects, and the joint torques are monitored to react in case an unexpected load is detected.
- Visual-compliant motion: In the final approach of the robot arm to its assembly position, the control mode switches to a visual-compliant motion. Visual servoing closes the outer loop to precisely position the arm, and with this position reference, an admittance controller closes the inner loop. This admittance (or inverse impedance) controller moves the robot along the desired trajectory allowing certain position error to minimize the load wrench applied at the end effector, based on feedback provided by the joint torque sensors.
- Force-Relaxation motion: When a kinematic chain is closed between two arms of the robot, during its locomotion along the spacecraft or in the final stages of assembly, one of the arms switches to force relaxation mode, where the robot adapts its position to minimize the load wrench relieving the possible stresses of the closed chain.

3.3 Vision system

Dedicated pose estimation sensors are required for the most critical basic operations: robot Manipulator Attachment and SMT/ORU Assembly. In these operations, an accurate estimation of the relative positions of the SMTs/ORUs is needed at least during the last phase of the approach (a few tens of centimeters). The approach adopted in MIRROR for precise positioning is based on the use of three vision cameras, installed near the end effector of the three legs (see Fig. 10), and fiducial markers installed in the SMTs/ORUs (see Fig. 13). In general, the eye-in-hand configuration provides enhanced visibility of the target, higher accuracy (since normally the camera can be placed closer to the target and in the most convenient pose for the estimation), and is more suitable for implementing visual servoing control algorithms.

In MIRROR, having the cameras installed on the limb end effectors ensures that the cameras can be freely positioned in 6DOF to acquire images from the most favorable position and orientation, making a dedicated pan-tilt system unnecessary.

When performing a Manipulator Attach operation, the camera of the limb to be attached has a direct view of the SMT manipulation SI in an axial direction, meaning that both SIs can be centered (radially) with high accuracy using an eye-in-hand visual servoing control algorithm (see Fig. 10).

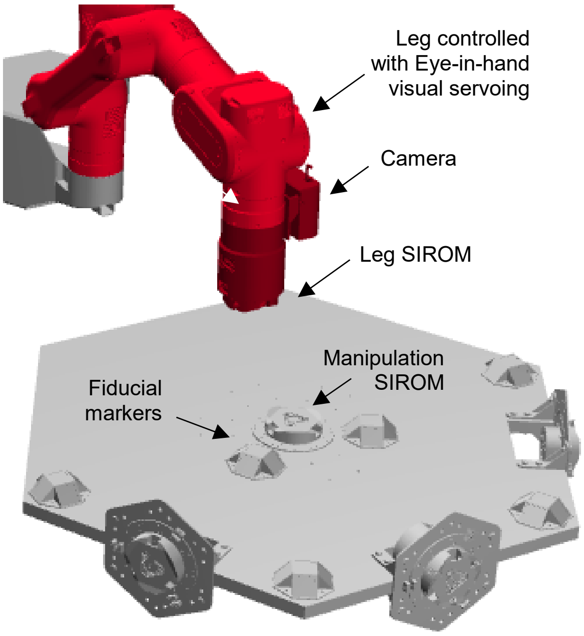

Figure 10 Manipulator Attach operation for grasping a SMT.

When performing a SMT/ORU Assembly operation, the cameras on the two working limbs (attached to the two parts to be assembled) cannot be used since they cannot see the assembly SIs. However, the third limb can be positioned to image the assembly SIs from the most advantageous points, providing feedback to an eye-in-head (external) type visual servoing algorithm (see Fig. 11). The camera on the third limb could even obtain images from several points to build an accurate estimation of the relative pose of the SMTs. Furthermore, it could also take images of the different pairs of SIs to be assembled, in the case of double and triple assemblies.

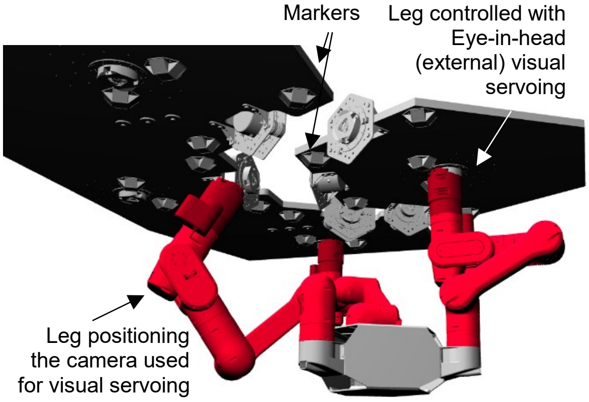

Figure 11 SMT Assembly operation.

Note that in case of camera failure, the two remaining cameras can be used to perform all the operations, simply using the camera of another leg in eye-in-head (external) mode when attaching the leg with the faulty camera. Then, this configuration is inherently redundant.

For the fiducial markers, a three-dimensional array of planar (AprilTag) markers is proposed (Fig. 13), due to its wide viewing angle limits (~ ±90º) and its simplicity. It is assumed that spacecraft attitude will be controlled attending to criteria such as energy generation, and not for providing favorable illumination during the operations. It is also likely that the assembly will happen in eclipse for thermal control reasons, meaning that no solar illumination will be present in order to allow detection of visual markers or other navigational aids. For this reason, active illumination systems have been included near each of the three cameras.

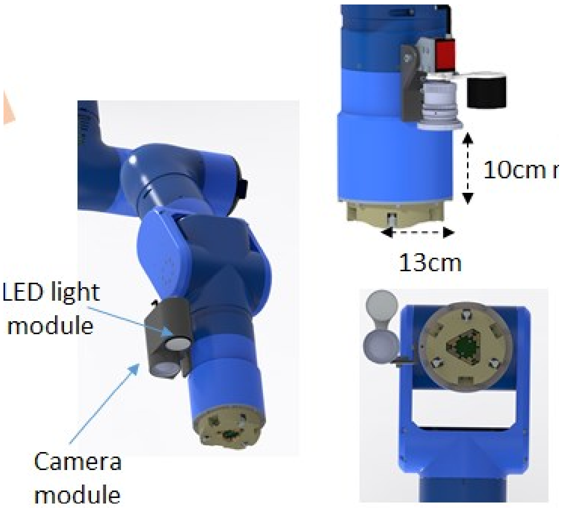

Figure 12 Camera and light module near the end effector (SIROM) of each leg.

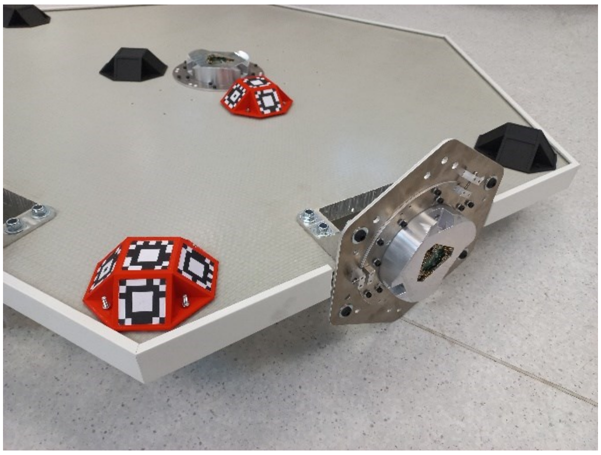

Figure 13 Three-dimensional array of planar markers installed in hexagonal SMT mock-up, near the assembly and manipulation SIROMs

In the first vision/control subsystem test the results shown in Tab. 1 have been obtained for the eye-in-hand visual servoing. These results show that in order to obtain sub-millimeter accuracy the camera has to be positioned at 30 cm from the markers, and that several markers have to be used simultaneously. Tab. 2 shows the error values obtained with an eye-in-head (external) visual servoing, when the camera is positioned with certain position/rotation errors. According to these tests, sub-millimeter errors can be expected in nominal working conditions.

Table 1 Eye-in-hand visual servoing accuracy results obtained during subsystem testing.

Distance Camera-marker [mm]	Number of 3D marker sets used	Position error [mm]	Angular error [deg]
600	3x3D sets	3.41	0.21
300	3x3D sets	0.83	0.11
300	1x3D sets	3.49	0.67
600	1x3D sets	17.36	0.92

Table 2 Eye-in-head (external) visual servoing accuracy results obtained during subsystem testing.

Camera Error X [m]	Camera Error Z [m]	Camera Error RotY [deg]	Position error [mm]	Angular error [deg]
0	0	0	0.30	0.08
0	-0.02	0	0.31	0.12
0	-0.04	0	0.39	0.15
0	-0.06	0	0.56	0.17
-0.02	0	0	0.61	0.17
-0.04	0	0	0.82	0.26
-0.06	0	0	1.03	0.34
0	0	-10	2.09	0.17
0	0	-20	8.79	1.46

3.4 SIROM Standard Interconnects

SIROM [7] is designed as an androgynous interface allowing easy mating/demating with other SIROMs. Its high capture latches are based on the docking system of ISS Columbus module. This, combined with its guiding petals, provide SIROM a self-aligning capability tolerant to very large misalignment conditions. Once mechanically latched, SIROM deploys its connectors board to establish a physical plug for data, electrical power transmission and fluid transmission (optionally).

Figure 14. Active (left) and passive (right) SIROMs.

Before delivery of SIROMs for integration in MIRROR testbed, the SIs (Standard Interface) have been validated at component level and consisted of the following tests:

- Electronics test
- Functional and electrical test
- Misalignment test
- Backdrive test
- Triple docking functional test

For the misalignment and backdrive tests, a test set up consisting of a robotic arm UR10 provided with an Active SIROM and a Passive SIROM mounted on workbench has been used (Fig. 15).

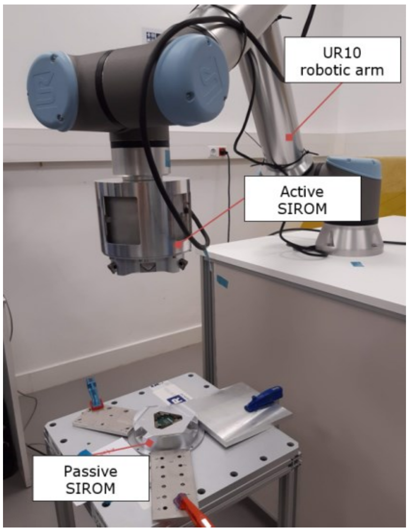

Figure 15. Misalignment and backdrive tests setup

The objective of the misalignment test was to test SIROM capabilities to mate a SIROM under different misalignments in all 6 degrees of freedom (X, Y, Z translations and Roll, Pitch, Yaw rotations). In particular, the latches and guiding petals design were tested and validated. A total of 76 different misalignment conditions have been evaluated, where the misalignments varied in the range specified in Table 1.

Table 1. Misalignment test conditions

Misalignment axis	Min.	Max.
X (radial, in-plane)	0 mm	+5 mm
Y (radial, in-plane)	0 mm	+5 mm
Z (connection axis)	+5 mm	+14 mm
Roll	0º	+9º
Pitch	-4º	+9
Yaw	0º	+9º

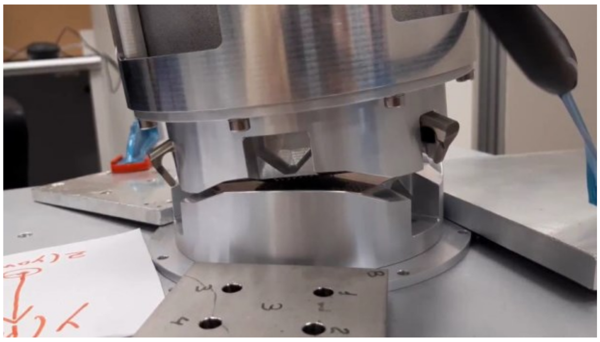

Figure 16. Misalignment test: Z=+7mm, pitch=5º

Regarding the backdrive test, it aimed to test the Active SIROM capabilities to mate a Passive SIROM under different robot backdrive conditions: this is, the robot is reacting against SIROMs latching, exerting force/moments in the opposite latching direction. The goal is to evaluate SIROM capabilities to overcome external forces that may arise during the mating operation of SIROMs due to mirror tiles mounting errors, robot control mode, forces induced by the compliant coupling between SI and tiles (used to avoid hyper-static stresses), etc. Here, the UR10 robot was controlled in force mode and SIROM demonstrated to have enough deliverable latches force to mate under external robot forces up to 100 N (X, Y and Z), torques up to 4 Nm in roll and pitch axes and 0.5 Nm in yaw axis. shows the force/torque measurement at the robot force/torque sensor place at its end-effector for one of the test cases.

Finally, a functional test was performed to demonstrate SIROM capabilities to perform triple docking/undocking of a hexagonal mirror tiles. Here, a setup consisting of a robotic arm UR10, five Active SIROMs, four Passive SIROMs and three hexagonal mirror mock-ups (1:1 scale) [8]. Positive results were obtained since several triple docking maneuvers were attempted and successfully performed, although the mirror structures seemed too flexible and thus, not representative of the final hardware. In [9], it can be seen a video of the triple docking functional test performed at SENER facilities.

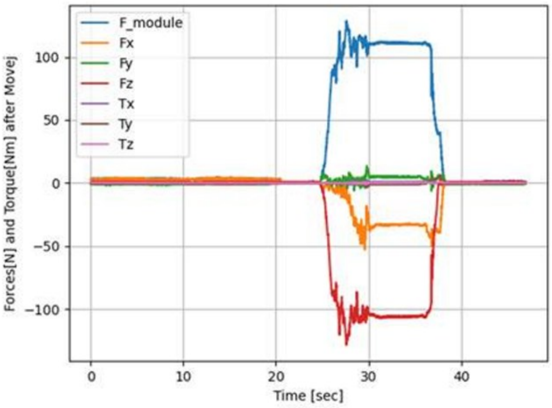

Figure 17. Backdrive test force/torque measurement

Figure 18. Triple docking functional test

4 BREADBOARD TESTING AND TESTBED DESIGN

MIRROR system tests are designed to validate the main operations, namely: a) locomotion of the manipulator across the structure, b) grasping of a structural element c) assembly of a structural element (SMT) making use of one, two and tree standard interconnects, and d) disassembly of a structural element (which could be needed for reconfiguration/repair purposes). The tests will focus on demonstrating that the system can achieve the required positional accuracy for the manipulation and assembly of the structure with an adequate level of robustness against structure inaccuracies and lighting conditions.

A testbed system has been developed for supporting the tests of the breadboard robot in laboratory environment. This testbed is composed of:

- SMT and reflector structure mock-ups, which are manipulated by the breadboard robot to simulate the on-orbit assembly process (see Fig. 19). The reflector structure simulates the part of the reflector that has been already assembled with several hexagonal SMTs.
- Weight compensation device, used to offload the weight of the reflector structure mock-up during the tests under 1-g. This system is composed of a

counterweight linked to the reflector structure mock-up through cables and pulleys, and an industrial manipulator that tracks the horizontal motion of the reflector (see Fig 20).

Note that the MIRROR breadboard robot body rests on the ground while the reflector structure mock-up "floats" above it. GMV's Hardware-In-The-Loop facility platform-art© provides support for testing, implementing part of the weight compensation and simulated sun illumination.

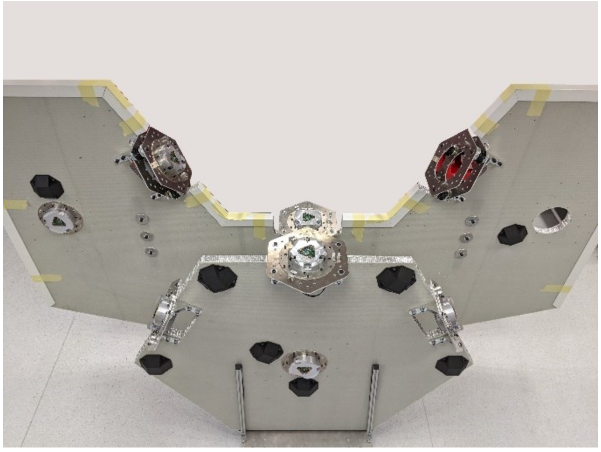

Figure 19. Single Mirror Tile mock-up (front) and Reflector Structure mock-up (back).

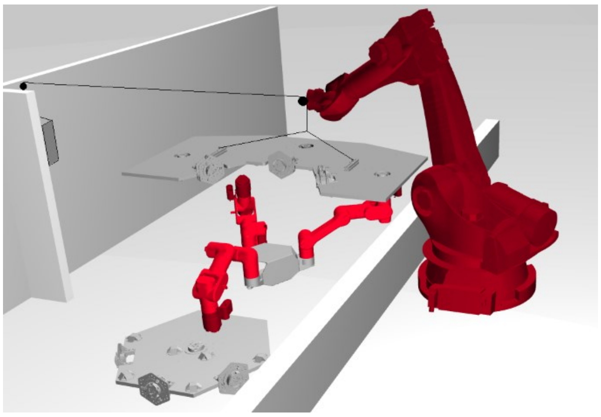

Figure 20. Experimental setup: Reflector structure mock-up supported by weight compensation system, breadboard robot and SMT mock up.

5 Conclusions

First vision/control subsystems tests indicate it is possible to achieve the required accuracy for in-orbit assembly of a telescope reflector structure. Also, SIROM subsystem tests have shown that the most complex foreseen assembly operation (assembly of a SMT through three SIROMs simultaneously) is feasible with current design. After completion of the current integration phase, the breadboard system test campaign is expected to demonstrate that the proposed MIRROR approach is a feasible solution for in-orbit structure assembly and spacecraft reconfiguration.

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