GROUND VALIDATION TESTING OF A RE-LOCATABLE MANIPULATOR FOR ON-ORBIT ASSEMBLY

A. Rodriguez[1], P. Romeo[2], I. Colmenarejo[3], J. Barrientos[4], J. Estremera[5], M. Lucia[6], A. Rusconi[7], G. Sangiovanni[8], S. Cordasco10, D. Antonucci11, A. Margan12, L. Baccielliere13, N.G. Tsagarakis[14], J. Viñals[15], M. Díaz-Carrasco[16] , L. Gerdes[17]

[1] *GMV, Isaac Newton 11 Tres Cantos 28760 - Spain,* areina@gmv.com
[2] *GMV, Isaac Newton 11 Tres Cantos 28760 - Spain,* pablo.romeo.m@gmv.com
[3] *GMV, Isaac Newton 11 Tres Cantos 28760 - Spain,* icolmenarejo@gmv.com
[4] *GMV, Isaac Newton 11 Tres Cantos 28760 - Spain,* jorge.barrientos.diez@gmv.com
[5]*GMV, Isaac Newton 11 Tres Cantos 28760 - Spain,* jestremera@gmv.com
[6] *Leonardo S.p.A., Viale Europa snc - 20014 Nerviano (MI) – Italy,* massimo.lucia@leonardocompany.com
[7] *Leonardo S.p.A., Viale Europa snc - 20014 Nerviano (MI) - Italy,* andrea.rusconi@leonardocompany.com
[8] *Leonardo S.p.A., Viale Europa snc - 20014 Nerviano (MI) - Italy,* guido.sangiovanni@leonardocompany.com
[9] *Istituto Italiano di Tecnologia, Via Morego, 30 16163 Genova – Italy,* stefano.cordasco@iit.it
[10] *Istituto Italiano di Tecnologia, Via Morego, 30 16163 Genova – Italy,* davide.antonucci@iit.it
[11] *Istituto Italiano di Tecnologia, Via Morego, 30 16163 Genova – Italy,* alessio.margan@iit.it
[12] *Istituto Italiano di Tecnologia, Via Morego, 30 16163 Genova – Italy,* lorenzo.baccielliere@iit.it
[13] *Istituto Italiano di Tecnologia, Via Morego, 30 16163 Genova – Italy,* nikos.tsagarakis@iit.it
[14] *SENER Aeroespacial, Avda. Zugazarte 56 Las Arenas 48930 - Spain,* javier.vinals@aeroespacial.sener
[15] *SENER Aeroespacial, Avda. Zugazarte 56 Las Arenas 48930 - Spain,* montserrat.diaz@aeroespacial.sener
[16] *ESA-ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands,* levin.gerdes@esa.int

ABSTRACT

This paper describes the design, development, and ground testing of the Multi-arm Installation Robot for Readying ORUS and Reflectors (MIRROR), a novel robotic system designed for on-orbit assembly and spacecraft servicing. MIRROR, composed of a Multi Arm Relocatable Manipulator featuring three identical robotic arms, aims to offer automated assembly capabilities, essential for the economical deployment and maintenance of extensive orbital structures. Ground testing focused on assembling Single Mirror Tiles (SMTs) to build the reflector of a large space telescope, emphasizing the manipulator's capability to assemble arbitrarily large structures and maneuver across them. The paper presents a comprehensive overview of the MIRROR system, outlines testing methodologies, analyses results, and discusses conclusions and insights gained from the ground validation tests.

1 INTRODUCTION

In recent years, the development of large-scale space structures has garnered significant interest from both space agencies and commercial stakeholders, who are exploring innovative and efficient methods for delivering their services in orbit [1].

Key on-orbit services include the removal, installation, and upgrading of multiple payload generations on large telecommunication or scientific platforms, as well as the assembly, maintenance, and decommissioning of large space-based solar power (SBSP) platforms [2] and telescopes [3]. To render these services technically and economically viable, automated assembly capabilities for the deployment and maintenance of extensive orbital structures will be essential.

Although several robotic systems for automated assembly have been proposed, many of them are based on fixed manipulators [4] or on mobile manipulators with limited capability for transporting the structural elements [5], thus restricting the ability to assemble arbitrarily large structures. Also, the simplicity of the assembly robot is often prioritized, resulting in systems with limited capability to assemble complex structures through dual manipulation [6] [7].

The Multi-arm Installation Robot for Readying ORUS and Reflectors (MIRROR) is an ESA-funded activity focusing on the design and ground testing of a robotic system for on-orbit structure assembly but also spacecraft servicing for maintenance, repairs, or upgrades. Currently, MIRROR has completed the manufacturing, assembly and integration of a multi-arm manipulator breadboard representative of the complete functionality, which is undergoing ground system testing. The primary objective of the tests is to demonstrate, under laboratory conditions, that the MIRROR robotic system is capable of assembling and disassembling arbitrarily large structures composed of structural/payload modules. This is achieved by demonstrating the following basic operations: a) manipulation of modules using Standard Interconnects (SIROMs) as manipulator end-effectors, b) locomotion of the robotic system across the structure being assembled, while eventually transporting structural/payload modules and c) assembly and disassembly of these modules at their final installation points. The ground tests are also intended to assess the performances of the vision-based control as well as its robustness against unfavorable lighting conditions and mechanical inaccuracies in the structure being assembled. Furthermore, the tests aim at validating the autonomy approach, which is based on executing automated and adaptive sequences of operations, along with the option to command the system at a lower level from the ground during non-nominal situations. This work presents a description of the MIRROR system, outlines the test plan, analyzes the test results, and presents conclusions and lessons learned during the testing process.

2 ON-ORBIT ASSEMBLY SCENARIO

MIRROR considers two different reference scenarios:

- The assembly of the reflector of a large space telescope.
- The reconfiguration of a modular spacecraft using Orbital Replaceable Units (ORUs).

The ground testing of the MIRROR breadboard system focuses in the first scenario, in which hexagonal structural/payload elements called Single Mirror Tiles (SMTs) are assembled to build the telescope reflector. The SMTs are equipped with assembly Standard Interconnects (SIs) located on the sides of the hexagon that allow assembling the SMTs to each other.

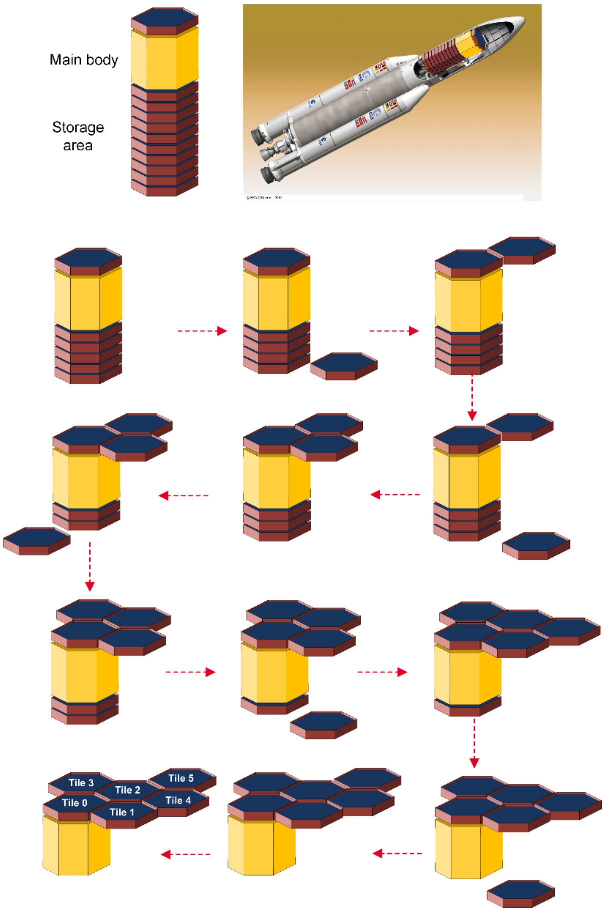

Figure 1: Sequence for the assembly of a telescope reflector with hexagonal SMTs.

The SMTs are also furnished with manipulation SIROMs located in the centre of the hexagon which permit the MIRROR robot to grasp and manipulate them.

Furthermore, the SIs provide data connectivity and power transmission between modules and towards the robot. These SMTs are initially stored in a depot in the telescope spacecraft (launch configuration), or in a different cargo spacecraft docked to the first one.

To assemble the reflector, a re-locatable manipulator with three identical arms is used. This manipulator is equipped with three SIs as end-effectors, which allow the robot manipulating the SMTs, walking across the structure and getting power/data from the spacecraft. Having three arms allows transporting a SMT to its assembly point with one arm while walking across the structure with the two remaining arms.

To assemble an arbitrarily large multi-ringed reflector (refer to Figure 1), three types of assembly operations are required, based on the number of SIs utilized concurrently for assembling one SMT: single, double, and triple assembly operations are needed since up to three SI pairs can be used simultaneously to assemble a SMT.

Additional details on the reference mission and concept of operations are provided in [8].

3 BREADBOARD ROBOT

The following subsections summarize the main characteristics of the MIRROR breadboard system. Additional details on the design are provided in [10].

3.1 Relocatable manipulator

The Multi Arm Relocatable Manipulator (MARM) consists of three identical 6-DOF robotic arms and a central torso to which the arms are connected. The primary component for realizing the MIRROR arms is the actuation unit that is used to power the joints of the robotic system. These actuation units integrate in a compact device a motor, reduction gear, brake, torque and position sensors and control electronics. The joint electronics implement joint position, torque and impedance control modes.

In order to ensure the correct execution of the real-time critical software components, a central embedded computer (EtherCAT Master) is dedicated to real-time motor control, sensor reading and other real-time devices operations [11].

The MARM also includes batteries and power distribution electronics that ensure that the robot can be powered both internally and externally through the power interface of its SIs end-effectors.

More details on the design and validation of the MARM can be found in [10].

3.2 High Level Control system and Autonomy

The high-level controller runs in an on-board PC-based Robot Control Unit. The controller software is based on the execution of On-Board Control Procedures, which encode the sequence of basic operations that are executed autonomously with some degree of adaptability to assemble a structure. These basic operations include the attachment of an arm to a SMT or to the spacecraft, the assembly of a SMT to the structure or the locomotion of the robot to the next attachment point on the structure. These operations are executed with enough accuracy and in a safe way thanks to a combination of visual servoing and impedance control.

The sequence for attaching an arm to a SMT for manipulation or for locomotion purposes is as follows (see Figure 2):

1) The arm end-effector SIROM is approached to the SMT SIROM using a path precomputed with an RRT* planner, to a close but still safe position.
2) Visual servoing is used to complete the approach of the end-effector SIROM, until it enters the capture volume of the SMT SIROM (a 5 mm radius, 15 mm long cylinder). The camera in the same arm is used for feedback (eye-in-hand visual servoing).
3) The SIROMs are latched until both SIROM fit together. The manipulator uses impedance control to allow this motion and to avoid fighting against the forces exerted by the latches.

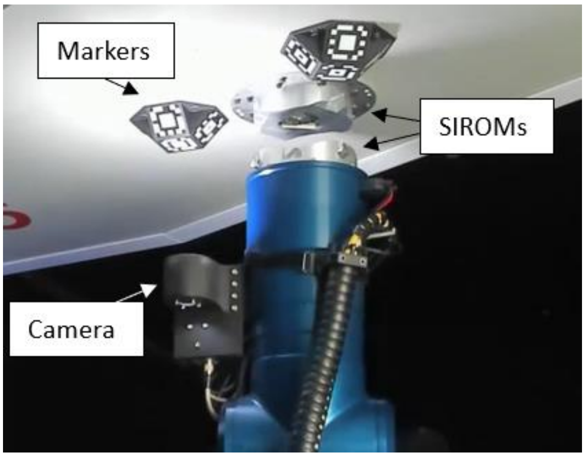

Figure 2: Arm attach (grasp) operation.

The sequence for assembling a SMT is similar (see Figure 3). In this case, one arm is attached to the structure, another is used to asssemble the SMT to the structure, and the camera on the third arm is used to provide vision feedback. In the case of a double or triple assembly, visual control needs to be accurate enough to ensure that the two or three assembly SIROMs in the SMT reach their capture volumes simultaneously (±2 mm, ±1.0 degree accuracy is needed for a triple assembly). Visual control can be combined with impedance control to make this operation safer, since the margin for completing a triple assembly without colliding is small (less than 10 mm).

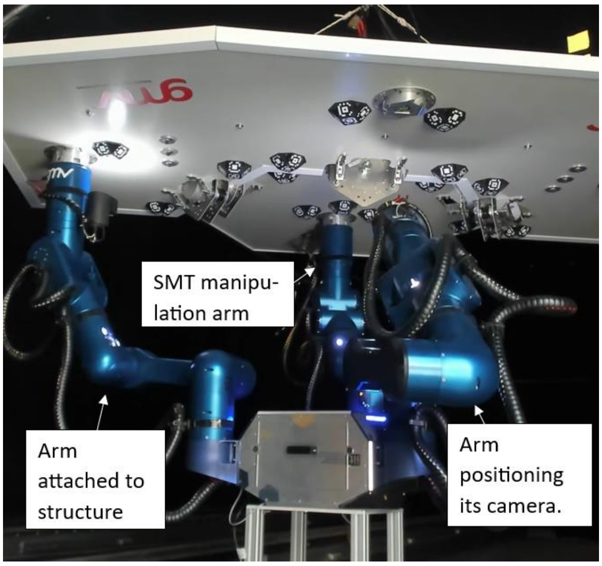

Figure 3: SMT Assembly operation.

The vision system is composed of three cameras installed near the end effectors of the three arms (see Figure 4). This design allows positioning the cameras conveniently for maximum visibility and provides redundancy against the loss of one camera.

Figure 4: Camera, light, and end-effector SIROM in one of the manipulator arms.

Fiducial markers are installed near the SIROMs used for manipulation/locomotion or for assembly. These markers are 3D arrangements of planar AprilTags, which allow estimating accurately their pose from a wide range of view angles. The cameras are equipped with lights to ensure that the fiducial markers will be correctly detected even in eclipse conditions.

Eye-in-hand or External Image Based Visual Servoing algorithms are used to reach the desired target poses accurately, depending on the operation to be executed, as explained previously.
More details on the vision system hardware, algorithms and performances can be found in [8].

3.3 Standard Interconnects

SIROM (Standard Interface for Robotic Manipulation) is the solution used as Standard Interconnect in the MIRROR project. The models used (Figure 5) are an evolution of the previous version of SIROM, developed by SENER since the H2020 0G5 call in 2016 [12].

Figure 5: SIROM active and passive models

SIROM provides mechanical coupling as well as power and data transfer between the two sides. The capture is done with high-range capture latches and alignment petals to ensure correct positioning of the passive side. Once the positioning is correct, the final movement of the operation deploys the connectors on top of the interface to make electrical connection.
The main features of the SIROM mechanism:

- Androgynous design: Active versions capable of capturing either a Passive or an identical configuration.
- Cost-optimized: Passive version designed to reduce costs when multiple matting ports are needed to be installed.
- The latches of the Active SIROM are responsible for capturing (before contact) the Passive SIROM and establishing the required preload to clamp the assembly.
- High-capture range latches based on the docking system for ISS. The mechanism includes three capture hooks (or latches) evenly distributed 120º apart.
- Self-aligning capability after contact using guiding petals.
- Compact design including data, electrical, and/or fluid transfer capabilities. Mass <1,5kg.

From the previous version, the SIROM has been modified for MIRROR to ensure the requirements of the mission are met. The most prominent modifications are:

- New design for guiding petals to allow up to 60º angle latching in triple-docking configuration.
- Two identical rear connectors in each SIROM for power and data which allow connecting the SIROMs in daisy chain.
- High-power connector added for robot batteries power supply, up to 16 A.
- New design for the connectors plate, providing 120º symmetry and 3 positions for latching that allow easier robot control.
- Connectors plate elevation mechanism to ensure POGO pins on top of the interface are deployed after the SIROMs are mechanically coupled.

These improvements made for MIRROR were tested internally and externally with successful results.
The integration of the breadboard model included 5 active SIROMs and 6 passive SIROMs. Of these, 3 active models were positioned as end effectors of each limb of the MARM. The rest were part of the SMT and spacecraft mock-ups used in tests.

4 TESTBED SYSTEM

4.1 MIRROR Testbed

The purpose of the MIRROR testbed is to provide a physical environment representative of the operational scenario during ground testing. The testbed is composed of the following elements:

- Mock-ups of an SMT and of the spacecraft structure, simulating the overall size/shape, mechanical and electrical interfaces (SIROMs) and visual properties (mainly the fiducial markers) of their flight counterparts. The SMT mock-up is a 1.2 m hexagon and includes three assembly SIROMs on three contiguous sides (see Figure 6), and a manipulation SIROM in its center. The spacecraft structure mock-up (see Figure 7) simulates the part of the structure that has been already assembled, resembling three SMTs interconnected with each other. It includes three manipulation SIROMs that can be used for testing the locomotion and up to three assembly SIROMs. Both the SMT mock-up and the structure mock-up can be configured to be assembled using one, two or three assembly SIROMs simultaneously, to test the different types of assembly operations. These mock-ups are constructed using lightweight and rigid aluminum and glass-fiber honeycomb panels. The mock-ups include fiducial markers installed near the assembly and manipulation SIROMs. The spacecraft structure mock-up provides electric power and connectivity to the robot through the manipulation SIROMs. Conversely, the robot provides power and commands/monitors the SMT during the manipulation and assembly process, through its manipulation SIROM.

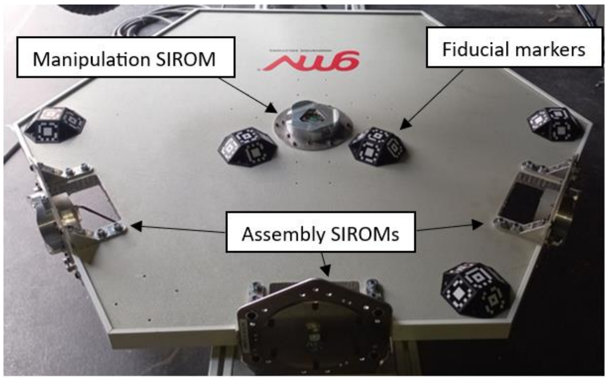

Figure 6: SMT mock-up.

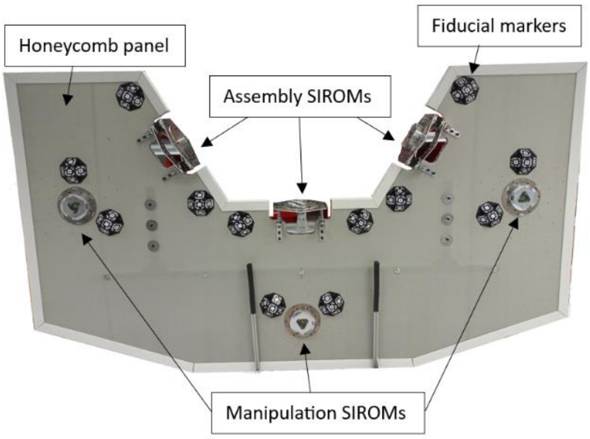

Figure 7: Spacecraft structure mock-up.

- A weight compensation device has been developed to simulate the Zero-G conditions of the actual scenario (see Figure 8). While the SMT mock-up (12 Kg) can be manipulated by the MIRROR robot under 1G, the structure mock-up (35 Kg) necessitates a compensation system. The weight compensation device consists of a counterweight, a cable, and low-friction pulleys. An industrial robot is employed to position one of these pulleys directly above the mock-up's center of mass, thereby ensuring that only vertical forces are exerted. The telemetry of the MIRROR robot is used to estimate the position of the center of masses of the mockup to command the industrial robot.

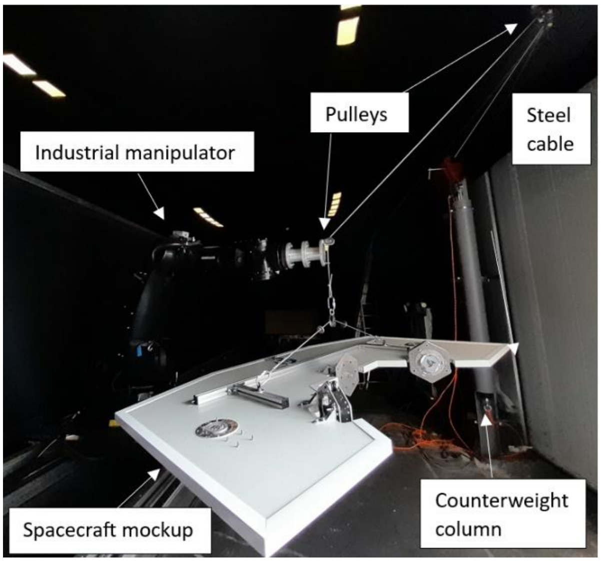

Figure 8: Weight compensation device holding the spacecraft structure mock-up.

4.2 *Test facility*

The facility used for the tests is GMV's platform-art hardware-in-the-loop testing laboratory [9]. This facility is equipped with industrial robots (one of them used to implement the weight compensation system) and an illumination system composed of a sun-representative spotlight mounted on a gantry cartesian manipulator. The laboratory is designed to provide an optical environment representative of on-orbit scenarios (low reflectivity) as shown in Figure 9.

4.3 *Test setup*

For the tests the MIRROR robot is fixed to a stand on the laboratory floor. One of the arms can reach a dedicated part of this stand simulating the spacecraft SMT depot. The spacecraft structure mockup is suspended above the robot with the help of the weight compensation device. This setup allows testing the locomotion of the robot across the structure without moving the robot. In addition, this setup allows applying weight compensation to the spacecraft mockup, which is much simpler than applying it to the robot since the position of its center of gravity would depend on its arm poses. Since none of the mockups to be assembled are fixed to the ground, their poses cannot be known with enough accuracy using proprioceptive sensors only (that is, without using the vision system).

Figure 9: Test setup in the platform-art testing facility, with the multi-arm manipulator attached to the spacecraft mockup and manipulating a SMT for assembling it.

5 SYSTEM TESTS

The validation approach at system level is based on the execution of the main MIRROR basic operations in the environment described above:

- Manipulator attachment and detachment: One of the robot manipulator end effectors is attached to a manipulation SIROM on the SMT or spacecraft structure mockups, using vision and compliant control, and later detached from it.
- Locomotion: The robot uses two manipulators that are alternatively attached/detached to the SIROMs in the structure mockup to move itself with respect to the structure.
- SMT simple/double/triple assembly and disassembly: The robot assembles the SMT to the structure using one/two/three assembly SIROMs simultaneously, and later disassembles it.

In addition, the following robustness tests are executed:

- Robustness to lighting conditions: an assembly test Is performed under three different illumination conditions: eclipse (i.e. scene illuminated with the robot lights only), sun shining directly onto the camera, sun producing direct specular reflection onto the camera.
- Robustness to inaccuracies in the structure: one of the assembly SIROMs on the spacecraft structure mockup is moved X mm to evaluate the impact on the triple assembly process.

This validation is complemented with additional tests performed in simulated environment, to overcome the limitations of the physical testbed.

6 TEST RESULTS

In this section, test results of assembly operations are shown since it includes the most critical functionalities of the control system: Visual Servoing that is in charge of precisely positioning the SMT in the already built structure, and force-based control, since contact forces are expected to appear during approach but have to be kept under reasonable values, and the robot has to be driven by assembly forces when SIROMs pull themselves together to complete a tile assembly.

The complete assembly procedure consists in three phases:

1. Free motion approach: The arm holding the SMT moves in position-based control through a joint-interpolated trajectory approaching the SMT to the assembly pose.
2. Visual Servoing camera fine approach: The free arm performs eye-in-hand visual servoing to place itself (and its camera) w.r.t. the scene,
3. Visual Servoing assembly approach: The SMT carrying arm performs eye-to-hand image-based visual servoing using the images provided by the free arm camera to complete the assembly approach, until the assembly SIROMs are within their capture range.
4. Compliant latching: The SMT carrying arm enters in low-impedance control mode, and the assembly SIROMs close their latches, completing the SMT assembly while the arm moves compliantly.

Performance data from the final two assembly steps is displayed in Figure 10 and Figure 11 to illustrate the key aspects of this operation.

Figure 10 shows the distance and angle between the frames of the mating faces of SMT and structure central assembly SIROMs in 10 triple-assembly runs during step 3 (Visual Servoing assembly approach). In ideal conditions, both frames should be coincident at the end of the assembly. However, these frames are extracted from the recorded images by reprojecting the design geometry between the fiducial markers and the frames, so an error due to manufacturing, assembly, and PnP from the reprojection are expected, which shows in the graphics being the final relative poses between both SIROMs 6 mm in distance norm, and 1.6 deg in total angle. Since the VS algorithm is image-based, the actual performance comparison must be measured against the reference image, which relative poses are shown by horizontal black lines. This leaves a mean final error (that includes the PnP reprojection) between reference pose and final pose of 2.7 mm and 0.17 deg. It is worth noting that orientation is matched rapidly and accurately before the first 10 seconds of the motion. However, around 5 seconds before the algorithm considers that the final pose has been reached with enough accuracy, this orientation has a sudden bump (of 0.17 deg), while the distance continues to decrease. This is due to the SIROMs colliding as it is shown on the contact force analysis.

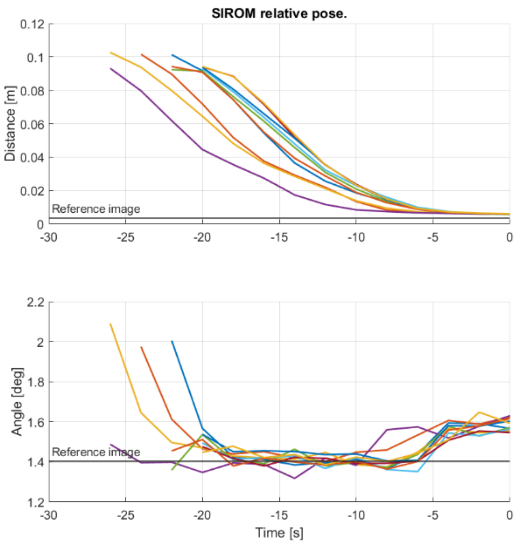

Figure 10: Distance and angle between assembly SIROMs during Visual Servoing (10 runs).

Figure 11 depicts the axial and radial loads on the central assembly SIROMs contact faces during the VS approach (blue area) and Compliant latching (green area) phases. These loads are computed through the joint torque sensors of the arm holding the structure, relating them to cartesian forces through the manipulator jacobian transpose $\tau = J(q)^T \cdot F$.

During the VS approach, a spike in contact loads happens at instant (a), where forces stay below 4N in both directions, and torques rise to around 7Nm axial and 5Nm radial. At instant (b), the SIROM petals engage, greatly rising the axial torque up to almost 15Nm while the radial component stays constant. This corresponds to the sudden bump of orientation error seen in Figure 10. At this point, the forces also increase in both directions, staying under 6N.

Once the visual servoing phase finishes, the arm enters in low-impedance control mode, which causes the arm to adapt to the previously applied loads, as it can be seen in the sudden drop of all loads at the beginning of the Compliant latching phase (except the radial torque that raises slightly). Once settled, the latches close at instant (c) and the active SIROM pulls the SMT and its carrying arm to the final assembly pose, increasing all loads. However, the loads exerted by the latches are the difference between the total loads measured and the ones existing before the grasping motion, which correspond to the static contact loads of both SIROMs. This results in a force increase of 4N radially and 3N axially, and a torque increase of 4Nm radially and 6Nm axially, which are low enough for the latches to close and successfully attach the SMT to the structure.

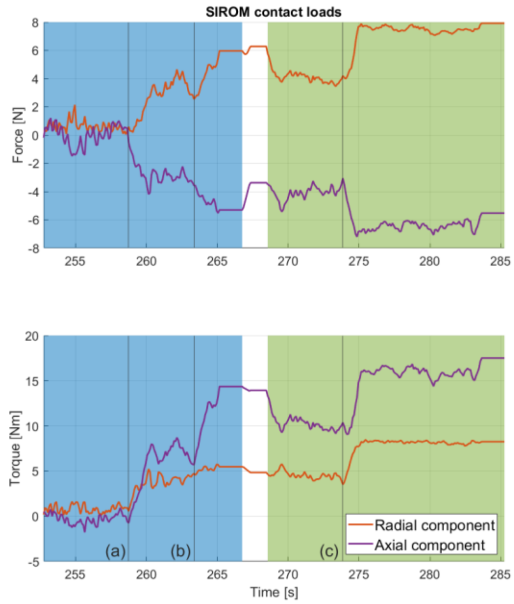

Figure 11: Contact loads between assembly SIROMs during the Visual Servoing and Compliant Grab phases.

7 CONCLUSIONS

This paper presents the breadboard prototype of a 3-limb relocatable robotic manipulator for the assembly and reconfiguration of space structures, which will enable their scalability and maintenance. Mock-ups of both spacecraft and SMT are described, as well as the testbed designed to perform technology validation tests under 1g conditions. System tests conducted are presented, focusing on the obtained data of two of the most critical aspects of the assembly operations: Visual Servoing and force-control motion. The results show that the MIRROR system is accurate and delicate enough to precisely position the SMT on its assembly position without damaging it nor the structure, and allowing the SIROMs to rigidly couple both mock-ups.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

1. Davis J. P., Mayberry J.P., and. Penn J. P., (2019). On-Orbit Servicing: Inspection, Repair, Refuel, Upgrade, And Assembly Of Satellites In Space, Aerospace.org

2. Gosavi, S.S, *et. al.*, (2021). A Review on Space Based Solar Power, Journal of Thermal Energy System, Volume-6, Issue-1.

3. Roa, M.A., *et al.* (2019). In-Space Robotic Assembly of Large Telescopes, *15th symposium on Advanced Space Technologies in Robotics and Automation*, ESA-ESTEC.

4. Komendera, E. E., and Dorsey, J. (2017). “Initial Validation of Robotic Operations for In-Space Assembly of a Large Solar Electric Propulsion Transport Vehicle,” in AIAA SPACE and Astronautics Forum and Exposition. Orlando, FL, 5248. doi:10.2514/6.2017-5248

5. Roa, M. A. et.al., (2022). PULSAR: Testing the Technologies for On-Orbit Assembly of a Large Telescope.

6. Nanjangud, A., *et al.*, (2019). Towards Robotic On-Orbit Assembly of Large Space Telescopes: Mission Architectures, Concepts, and Analyses, 70th International Astronautical Congress (IAC), Washington D.C., USA.

7. Flores-Abad, A., Maa, O., Pham, K., Ulrich, S. (2014). A review of space robotics technologies for on-orbit servicing. *Progress in Aerospace Sciences*, Volume 68.

8. Estremera, J. et al, (2022). Re-Locatable Manipulator For On-Orbit Assembly And Servicing, 16th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA) 2022

9. Casas, A., Tomassini, A., Gandia, F. (2005). PLATFORM: An Integrated Approach to Robotics and Space Navigation Validation. Designing and Setting the Robotic Test-Bed. SAIRAS 2005, 603. 40.

10. Hoffman, M., et al., (2023). Design and Validation of a Multi-Arm Relocatable Manipulator for Space Applications. ICRA 2023.

11. D. Antonucci et al. (2023). A Real-Time computer architecture based on a client-server approach for a Multi-arm Robot Manipulation (MARM) Platform 17th Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA) 2023

12. J. Viñals, J. Gala, and G. Guerra, “Standard interface for robotic manipulation (SIROM): Src h2020 og5 final results-future upgrades and applications,” in International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), 2020