EXECUTIVE SUMMARY REPORT

MIRROR

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DOCUMENT STATUS SHEET

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1.0	17/07/2023	37	Version produced for MIRROR final Acceptance
1.1	20/12/2023	37	Version for Final Acceptance Close Out implementing FA RIDS: • MV-009: Sections 7.2.4 and 8 updated

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1. INTRODUCTION

1.1. PURPOSE

The purpose of this document is to summarize the findings of the Multi-arm Installation Robot for Readying ORUS and Reflectors (MIRROR).

Note that sections 5.1.1 and 5.1.4 include contents by Leonardo/IIT and SENER respectively.

1.2. SCOPE

This document is applicable to the Multi-arm Installation Robot for Readying ORUS and Reflectors (MIRROR) project. The document is organized as follows:

- Section 1 presents the introduction of this document.
- Section 2 lists the applicable and reference documents.
- Section 3 introduces the MIRROR system.
- Section 4 describes the MIRROR operation concept.
- Section 5 presents the MIRROR design.
- Section 6 presents the MIRROR simulator.
- Section 7 describes the testing approach and main test results.
- Section 8 summarizes the main lessons learnt during the activity.
- Section 9 presents some conclusions.

1.3. DEFINITIONS AND ACRONYMS

1.3.1.DEFINITIONS

Concepts and terms used in this document and needing a definition are included in the following table:

Table 1-1 Definitions

Concept / Term	Definition

1.3.2.ACRONYMS

Acronyms used in this document and needing a definition are included in the following table:

Table 1-2 Acronyms

Acronym	Definition
BB	Breadboard
EGSE	Electronic Ground Segment Equipment
ESS	Energy Storage System
FDIR	Failure Detection, Isolation and Recovery
HDRM	Hold Down Release Mechanism
KDG	Kinematic, Dynamic and Graphic
OBCP	On-Board Control Procedure
ORU	Orbital Replacement Unit
PDB	Power and Data Bus
PDU	Power Distribution Unit
MIRROR	Multi-Arm Installation Robot For Readying ORUS And Reflectors

Acronym	Definition
MCCI	Motion Control Central Interface Board
MPSOC	Multi-Processor System On Chip Board
RCU	Robot Control Unit
SCU	Servo Control Unit
SCMU	Spacecraft Mock-up
SI	Standard Interconnect
SI_SS	Standard Interconnect Subsystem
SME_SS	Structural, Mechanical and Electrical Subsystem
SMT	Single Mirror Tile
SMTMU	Single Mirror Tile Mock-up
SNC_SS	Sensoring, Navigation and Control Subsystem
TB	Testbed
TB_SS	Testbed Subsystem
TBC	To be confirmed
TBD	To be defined
TC	Tele-command
TM	Telemetry
WCD	Weight Compensation Device

2. REFERENCES

2.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.x]:

Table 2-1 Applicable Documents

Ref.	Title	Code	Version	Date
[AD.1]	Cover letter AO 9908	AO 9908		
[AD.2]	Appendix 1- SOW AO 9908	AO 9908		
[AD.3]	Appendix 2- Draft Contract AO 9908	AO 9908		
[AD.4]	Appendix 3- Special Tender conditions AO 9908	AO 9908		
[AD.5]	GMV's MIRROR Multi-Arm Installation Robot For Readying ORUS And Reflectors	GMV 12452/19 V1/19	1.0	September 20th, 2019
[AD.6]	H2020 PULSAR D4.1 System Requirement Document (SRD)	D4.1 H2020_PULSAR-TAS-D11.1c	v3.2	31/05/2019
[AD.7]	H2020 PULSAR D4.1 - D11.1A-Mission Analysis	H2020_PULSAR-TAS-D11.1a Mission Analysis v2.4 TAS-F	v2.4	24/07/2019
[AD.8]	MIRROR System Requirements	MIRROR-SSS-GMV-0001	2.0	04/12/2020

2.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.x]:

Table 2-2 Reference Documents

Ref.	Title	Code	Version	Date
[RD.1]	MIRROR Concept of Operations	MIRROR-TN-GMV-0001	2.0	04/11/2020
[RD.2]	MIRROR System Requirements Document	MIRROR-SSS-GMV-0001	2.0	04/12/2020
[RD.3]	System Design Document	MIRROR-SSD-LDO-0001	RevB	11/01/2021
[RD.4]	Structural, Mechanical and Electric Subsystem Preliminary Design	MIRROR-PDD-LDO-0001	RevB	11/01/2021
[RD.5]	Control Subsystem Preliminary Design	MIRROR-PDD-GMV-0001	1.1	04/12/2020
[RD.6]	Sensoring and Navigation Subsystem Preliminary Design	MIRROR-PDD-GMV-0002	1.1	04/12/2020
[RD.7]	Standard Interconnect Subsystem Preliminary Design	MIRROR-SSD-SEN-0001	Rev2	03/12/2020
[RD.8]	MIRROR Breadboard Detailed Design Document	MIRROR-SSD-GMV-0001	1.2	28/06/2021
[RD.9]	MIRROR Structural, Mechanical and Electric Subsystem Detailed Design	MIRROR-PDD-LDO-0002	RevB	12/05/2021
[RD.10]	Standard Interconnect Subsystem Breadboard Detailed Design	MIRROR-DDD-SEN-0001	2.0	11/05/2021
[RD.11]	MIRROR Test Procedures Document	MIRROR-TP-GMV-00001	1.2	17/07/2023
[RD.12]	MIRROR Structural, Mechanical and Electric Subsystem Test Procedure	MIRROR-TP-LDO-0001	A	12/07/2022
[RD.13]	SIROM Subsystem Test Procedure	MIRROR-TP-SEN-00001	1	31/05/2022
[RD.14]	MIRROR Breadboard User Manual	MIRROR-MAN-GMV-00001	1.2	17/07/2023
[RD.15]	MIRROR Structural, Mechanical and Electric Subsystem User Manual	MIRROR-MAN-LDO-0001	A	12/07/2022
[RD.16]	SIROM User Manual	MIRROR-MAN-SEN-0001	1	26/05/2022

Ref.	Title	Code	Version	Date
[RD.17]	MIRROR Breadboard Test Report	MIRROR-TR-GMV-00001	1.0	17/07/2023
[RD.18]	MIRROR Structural, Mechanical and Electric Subsystem Test Results	MIRROR-TR-LDO-00001	Rev A	14/07/2023
[RD.19]	SIROM Subsystem Test Results	MIRROR-TR-SEN-00001	1	08/06/2022
[RD.20]	Technology Achievement Summary	MIRROR-RP-GMV-00001	1.0	17/07/2023
[RD.21]	Final Presentation	MIRROR-PRS-GMV-00001	1.0	17/07/2023
[RD.22]	Summary Report / Executive Summary Report	MIRROR-RP-GMV-00002	1.0	17/07/2023
[RD.23]	Final Report	MIRROR-RP-GMV-00003	1.0	17/07/2023

3. INTRODUCTION

Large structures in space are an essential and recurring element for space exploitation and exploration. Space structures are continuously increasing in size to bring increased economic and scientific benefits.

By providing in-space assembly capability through a mobile robotic manipulator, and making use of standard interconnect devices for mechanical coupling and data, power and fluidic interchange, MIRROR may bring the following capabilities to in-space servicing missions:

- **In-space assembly of telescope mirrors/reflectors and other large structures**: The MIRROR system makes possible the assembly of arbitrarily large telescope mirrors, which parts could be even disposed by several launchers.
- **In-space reconfiguration of modular spacecraft**: MIRROR provides capability to install, remove and replace ORUs with versatility and the possibility of moving across any serviced structure, if enough standard interconnects are available for locomotion purposes.

4. OPERATION CONCEPT

4.1. REFERENCE MISSION SCENARIOS

4.1.1. SCENARIO 1: ASSEMBLY OF SMT REFLECTORS

The reference mission focuses on a highly autonomous mobile robotic system, particularly a **multi arm relocatable manipulator,** for the assembly of a **multi-ring SMTd reflector** in **L2 point**. The relocatable manipulator has not only the capability to manipulate the reflector Single Mirror SMTs (SMTs) to be installed but also of moving itself across a structure while transporting the SMTs, thanks to its **three limbs equipped with standard interconnects (SI)**. The SIs provide mechanical coupling, which allows the manipulators to grasp the SMTs and allows assembling a SMT to the structure. SIs also provide power and data interfaces between the manipulator and the SMTs, between SMTs, and between the SMTs and the spacecraft main body.

The spacecraft is composed of a main body and a set of SMTs (see Figure 4-1) used to assemble the telescope mirror. The main body on the spacecraft is considered the starting point for the assembly of the telescope mirror (see Figure 4-2).

The SIs installed on the spacecraft (including the SMTs and the main body) and on the MIRROR manipulator provide mechanical, electric (power) and data interfaces between SMTs and between the MIRROR robot and the spacecraft.

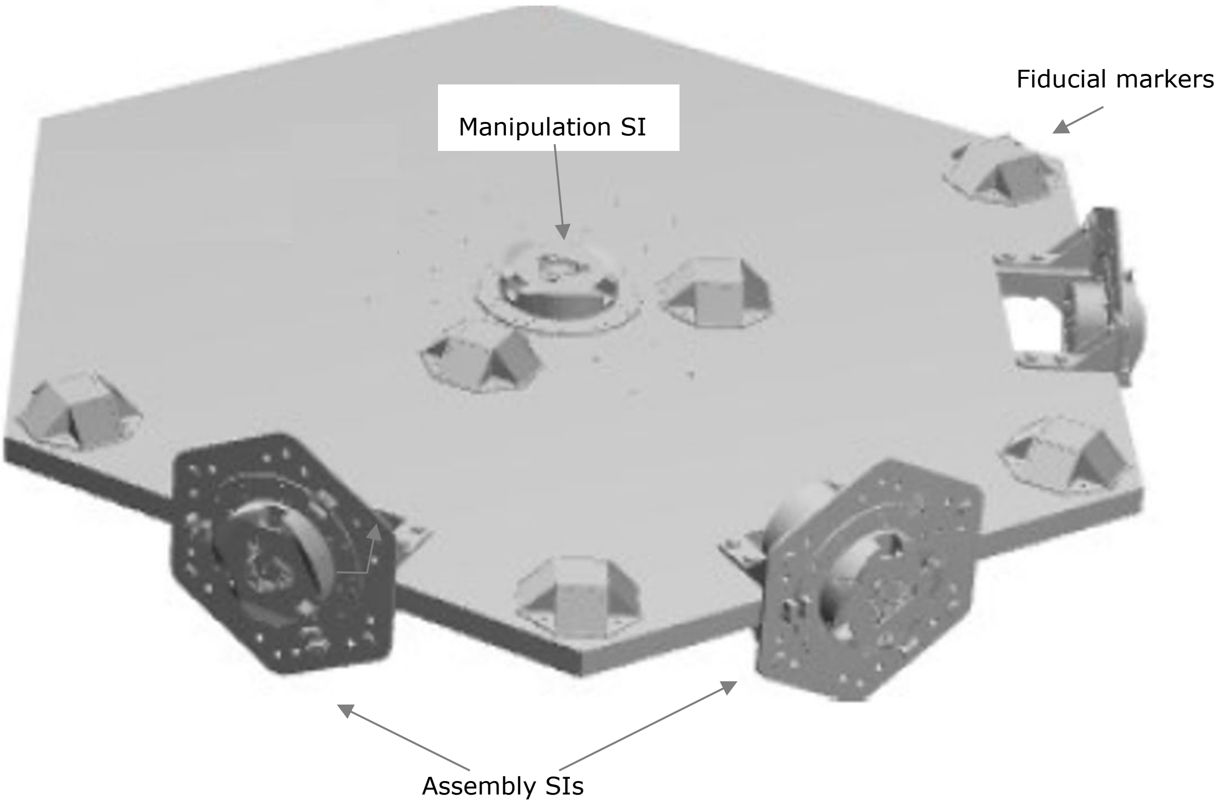


Figure 4-1 MIRROR reflector SMT parts

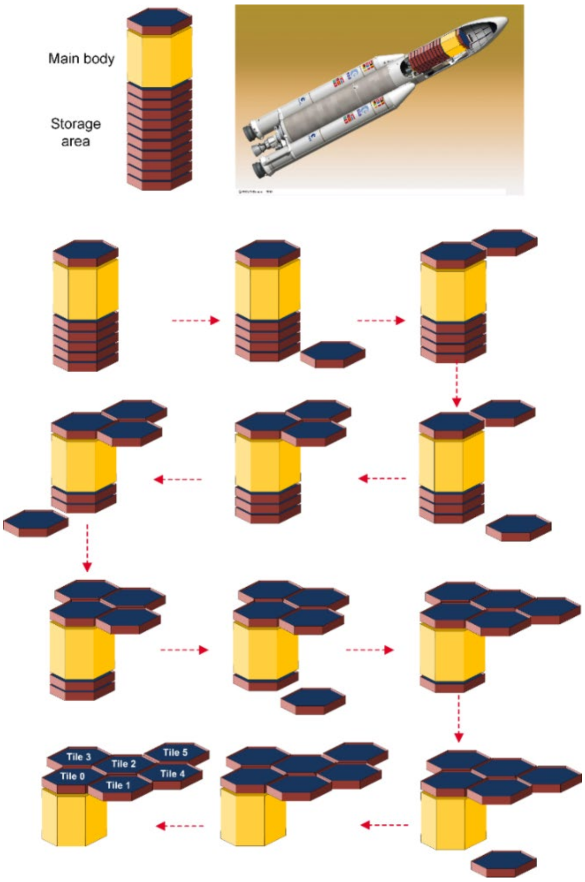


Figure 4-2 MIRROR reference mission scenario for assembly of reflectors

The assembly sequence implies the following assembly operations (see Figure 4-3):

- Simple SMT Assembly: a SMT is assembled to the structure by means of one of its assembly SIs.
- Double SMT Assembly: two contiguous assembly Sis are used for the assembly.
- Triple SMT Assembly: three contiguous assembly SIs of a SMT are used simultaneously for the assembly.

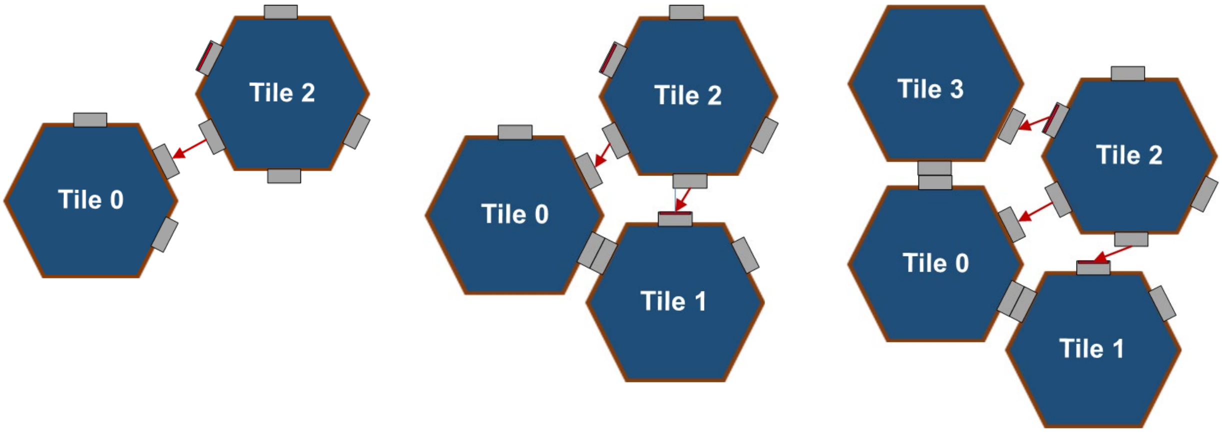


Figure 4-3 Assembly types: Simple (left), Double (centre), Triple (right)

4.1.2. SCENARIO 2: RECONFIGURATION OF MODULAR SPACECRAFT

The proposed mission for MIRROR Scenario 2 consists in **upgrading, reconfiguring and repairing an operational modular spacecraft, such as a GEO telecommunication satellite**. The aim of this scenario is to modify the functionality of a satellite by adding/replacing modules available on-board or provided by another servicing satellite. Specifically, this scenario deals with the hardware reconfiguration of a highly modular, maintainable, extendable satellite system according to a defined and simulated plan as well as manipulation of functional modules, which are coupled via SIs on the satellite platform.

This reference scenario is composed of the following elements:

- A servicer spacecraft, hosting the relocatable manipulator and the modules for upgrading/repairing, and
- A serviced spacecraft, with a modular design allowing reconfiguration.

The operations in this scenario would include two phases:

- Addition of modules. (e.g. telecommunications, hosted payloads, or dedicated modules for power generation, propulsion, etc.).
- Removal and storage of obsolete payload modules.
- Replacement of obsolete payload modules.

Note that only the first scenario was tested in the breadboard system.

4.2. DEFINITION OF OPERATIONS

Independently of the scenario, the MIRROR system executes the following high-level operations to accomplish its mission:

1) Deployment and Checkout. The multi-arm relocatable manipulator is commissioned to accomplish its main tasks.
2) Telescope Assembly or Spacecraft Reconfiguration operations, depending on the scenario.
3) Locomotion to robot base.
4) Stowage. The robot is stowed on its base on the spacecraft main body and transitions to a survival state in which it can remain for an extended period.

The Telescope Assembly high-level operation is defined according to the following sequence:

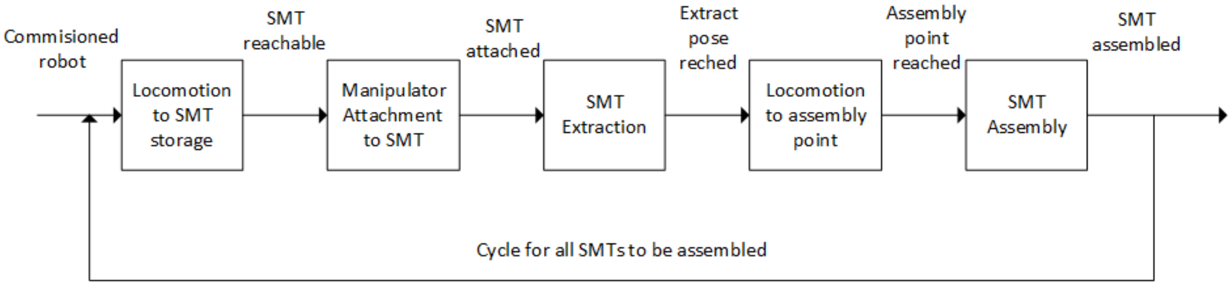


Figure 4-4 Telescope Assembly Operations Sequence

The Spacecraft Reconfiguration high-level operation is defined according to the sequence depicted in Figure 4-5.

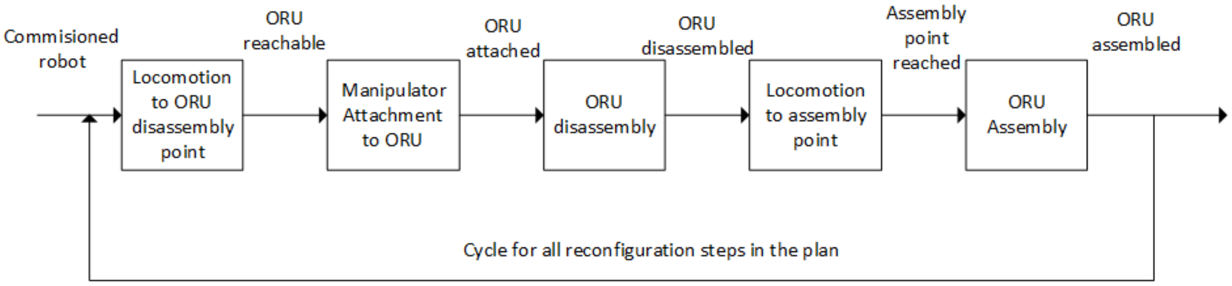


Figure 4-5 Spacecraft Reconfiguration Operations Sequence

The mission high-level operations for the two defined scenarios are accomplished through the execution of the following basic operations:

- Manipulator Attachment.
- Manipulator Detachment.
- Locomotion
- SMT/ORU Extraction.
- SMT/ORU Assembly.
- SMT/ORU Disassembly.
- Deployment and Checkout.
- Stowage.

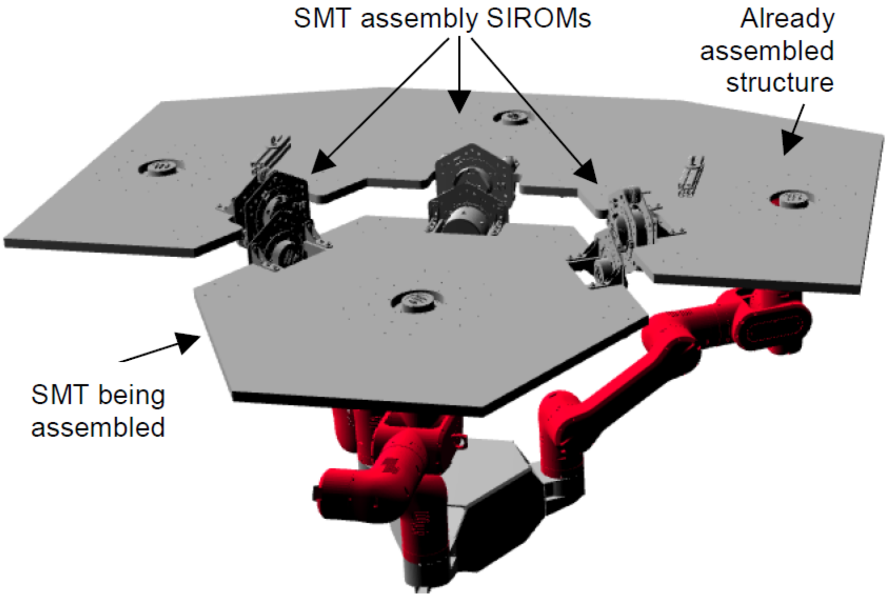


Figure 4-6 SMT Assembly basic operation.

4.3. AUTONOMY AND FDIR

It is assumed that in MIRROR reference mission, designed to operate in L2 point of Sun-Earth system (Scenario 1) or in GEO (Scenario 2), communication with ground does not suffer from large delays, limited bandwidth, or limited communication windows. Then, since ground control can be in the loop at least for making high-level decisions during the assembly process, a high level of autonomy is not justified. The MIRROR controller implements E3 Autonomy Level controller based on the use of On-Board Control Procedures (OBCPs). OBCPs are typically scripts that execute routine/recovery operations interacting in a safe and controlled manner with the rest of the system.

The **MIRROR FDIR system** can perform the following fault detection functions:

- Periodic system health monitoring.
- Specific checks during nominal procedure execution, to detect operational failures.

5. MIRROR DESIGN

5.1. RE-LOCATABLE MANIPULATOR

The MIRROR system is composed of the subsystems and components depicted in the MIRROR product tree as shown in Figure 5-1.

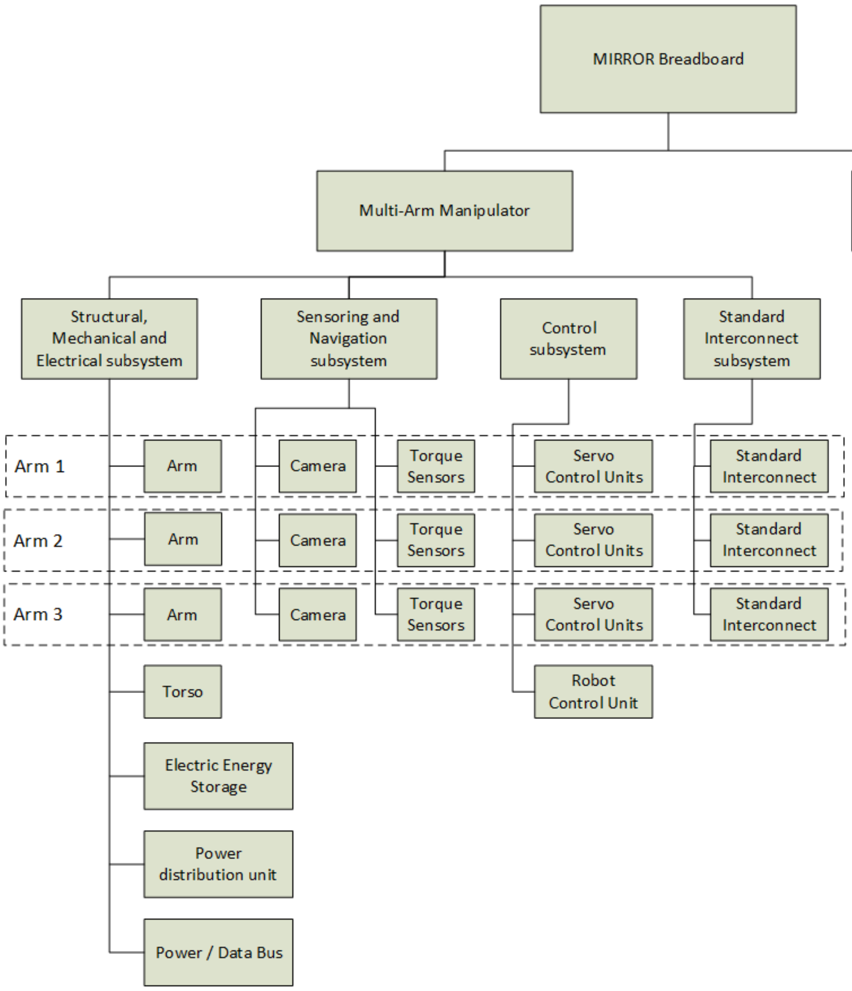


Figure 5-1: MIRROR Breadboard System product tree

The MIRROR Breadboard System includes the following subsystems:

- The Structural, Mechanical and Electric Subsystem.
- The Sensoring and Navigation Subsystem.
- The Control Subsystem.
- The Standard Interconnect Subsystem.
- The related EGSE equipment and software needed to monitor and control the MIRROR breadboard, including the Monitoring and Control Station, the power supply and the Emergency Switch.

5.1.1. STRUCTURAL, MECHANICAL AND ELECTRIC SUBSYSTEM

5.1.1.1. JOINT MECHANICS

The primary component for realizing the MIRROR limb kinematics is the actuation 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 simulations. Based on this, IIT designed two sizes of actuation module that were scaled/tuned to provide the torque demands identified. The two actuator sizes, "A" and "B" were inherited from the foundation actuation family developed in previous projects at the HHCM lab in IIT. The final design of the two actuation modules is shown in Figure 5-2. A torque sensing load cell is mounted between the output link and the harmonic reduction drive.

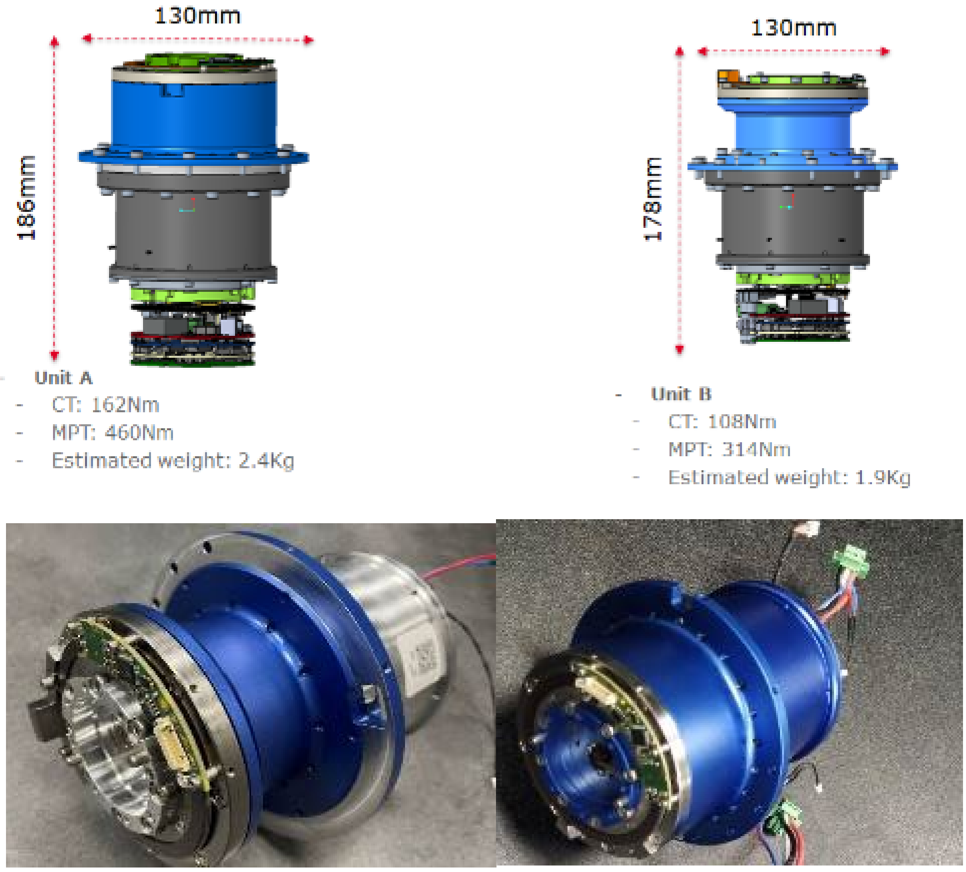


Figure 5-2: The two actuation modules "A" and "B" showing their main specifications and common mounting interfaces. At the bottom the two prototypes of size A and B drives.

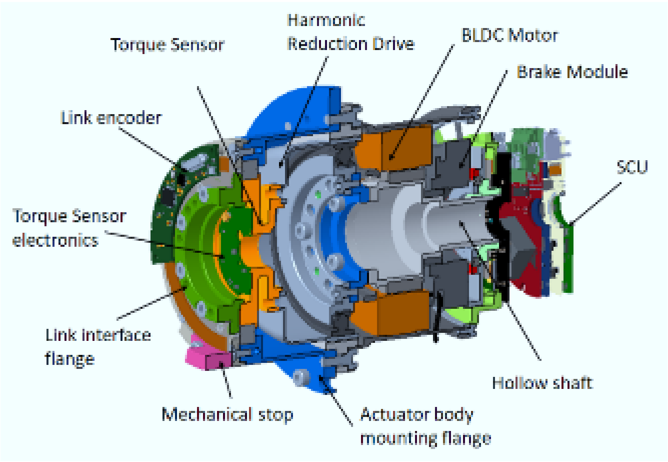


Figure 5-3: Cross section of the MIRROR drive showing the main components of the actuator.

5.1.1.2. JOINT ELECTRONICS

The SCU electronics are tightly integrated at the back of the actuator body facilitating the interconnections and cabling between the SCU and the actuator. This distributed architecture, with the SCU electronics incorporated into the joints, eliminates the need for multi-wire cable harnesses, thereby saving system mass and increasing system reliability, improves robustness with respect to EMC, having joint electronics located close to the sensors and the actuators, and still provides the needed data exchange frequency, satisfying control system bandwidth requirements.

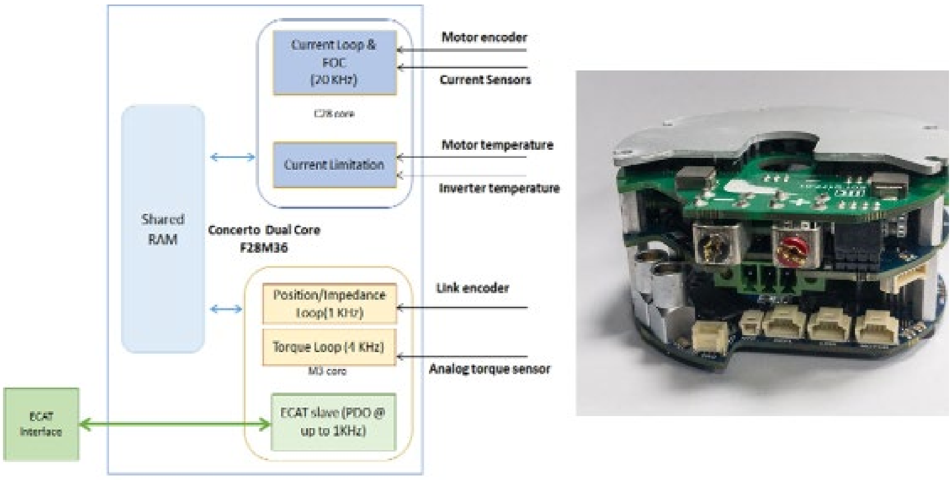


Figure 5-4: MIRROR actuation motor driver electronics.

5.1.1.3. JOINT DECENTRALIZED CONTROL

The SCUs execute the lower-level joint control, which provide two control modes including joint impedance and position regulators, Figure 5-5 and Figure 5-6. The most inner loop in both control schemes realize the motor current regulator, which with the functionality of a field-oriented control renders the required current to the motor of the actuation drive. In the joint impedance control, the outer most loop executes an impedance controller upon a torque regulator.

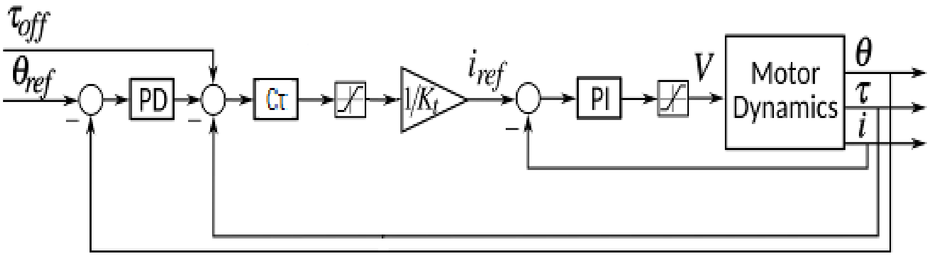


Figure 5-5: Overview of the overall decentralized control scheme implemented in the SCUs for the joint impedance regulation.

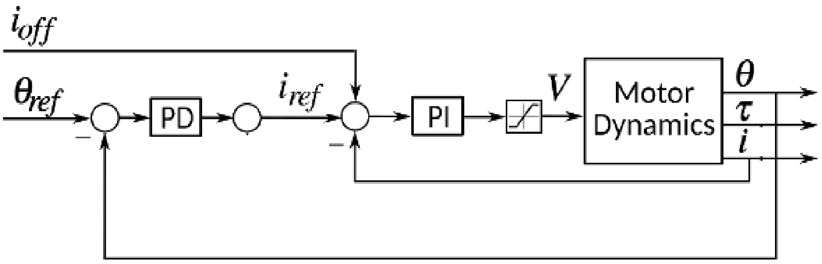


Figure 5-6: Control scheme realized in the SCUs to implement the position control functionality.

5.1.1.4. MIRROR LIMB BODY ELEMENTS

The kinematics of the MIRROR limb are implemented using two types of 2DOF body modules. The first type suggests the integration two actuators forming an "L-shape" 2DOF module and a "T-Shape" 2DOF body module (see Figure 5-7). The realization of the MIRROR 2DOF body modules implements an exoskeleton structure approach in which the body of the actuators is floating inside the exoskeleton structure.

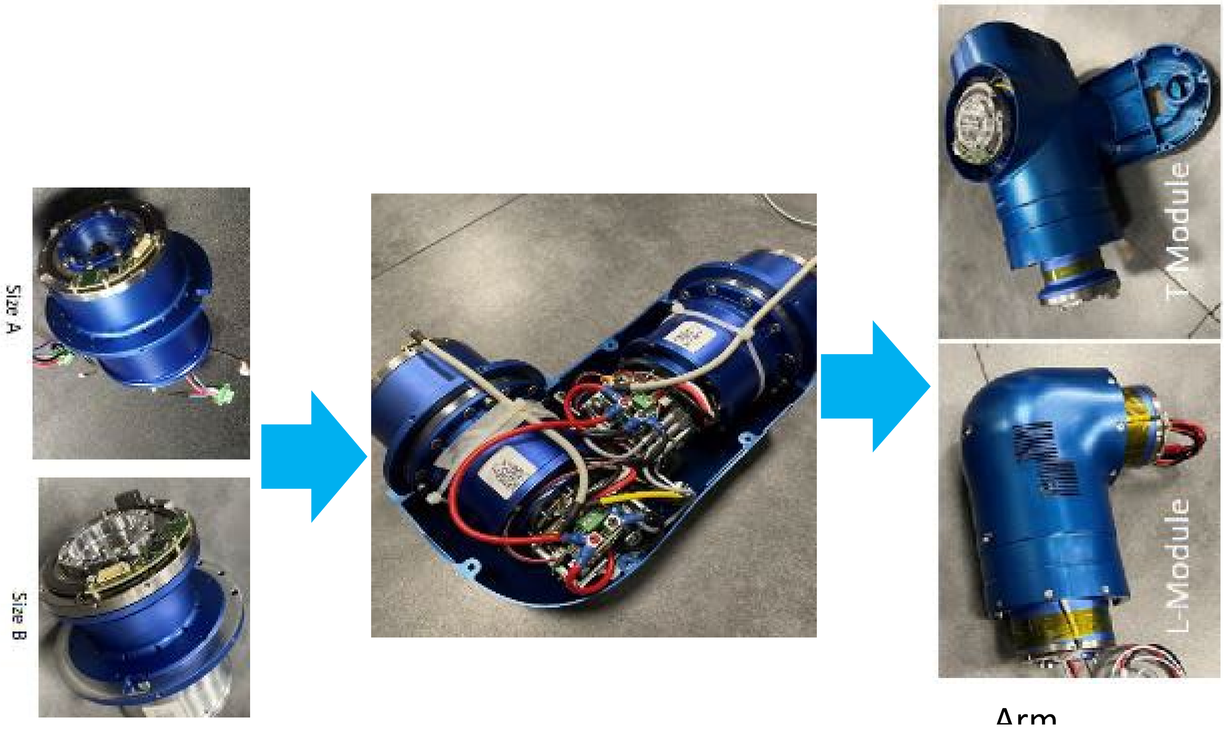


Figure 5-7: L-Shape and T-Shape modules designed for the realization of the MIRROR limb.

5.1.1.5. MIRROR PELVIS BODY

The pelvis body is the central body of the MIRROR breadboard, (see

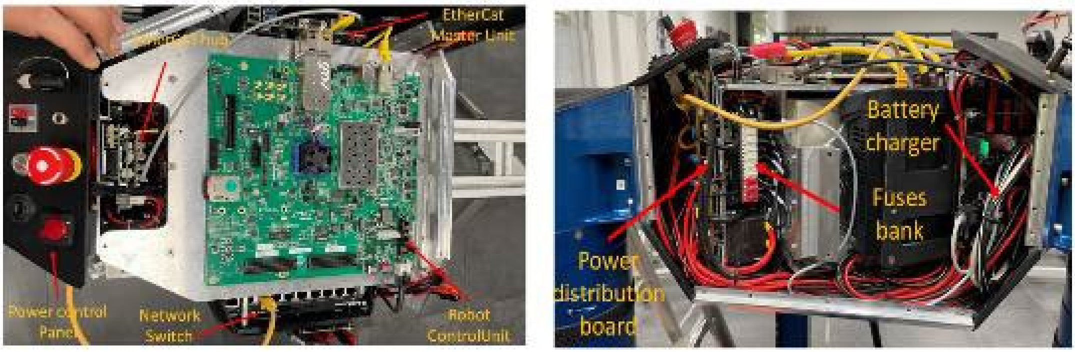


Figure 5-8). It is constituted of a triangular metallic structure, which allows the equal positioning of the three robotic limbs on its corners. The structure hosts the RCU and the EtherCAT Master Communication Unit (MCU), with all their electronics boards and external box, a network switch, the battery envelope and the charge and discharge unit.

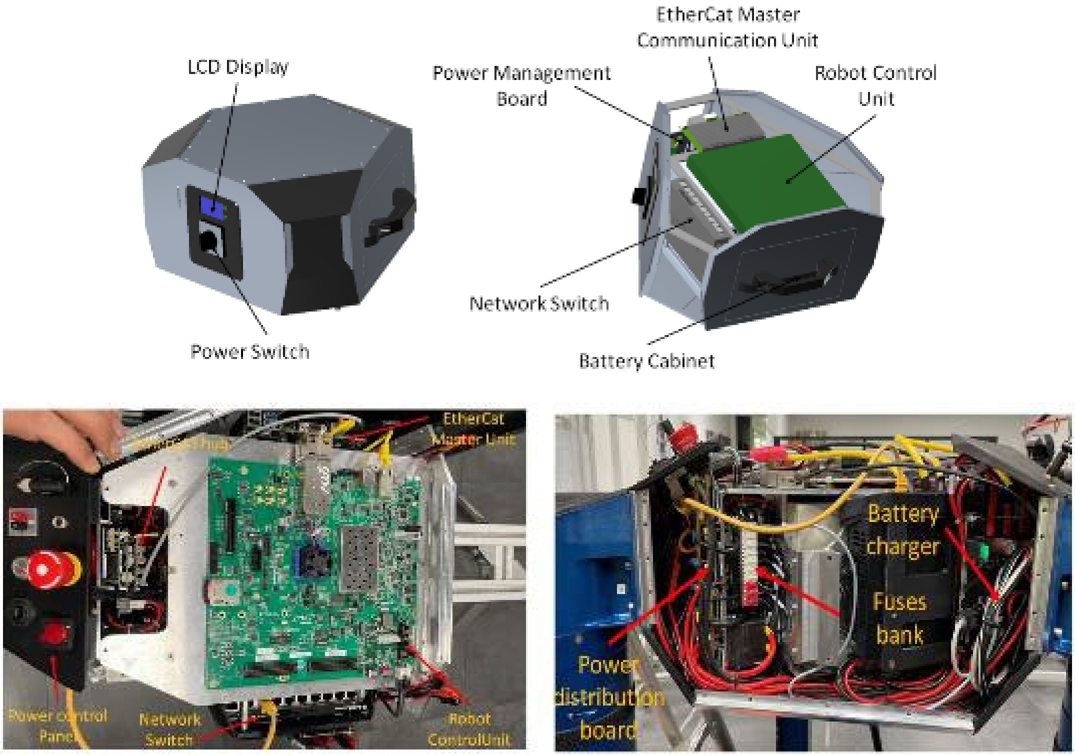


Figure 5-8: MIRROR pelvis body CAD and breadboard showing the arrangement of the main components.

An overview of the dimensions of the MIRROR robot is introduced below.

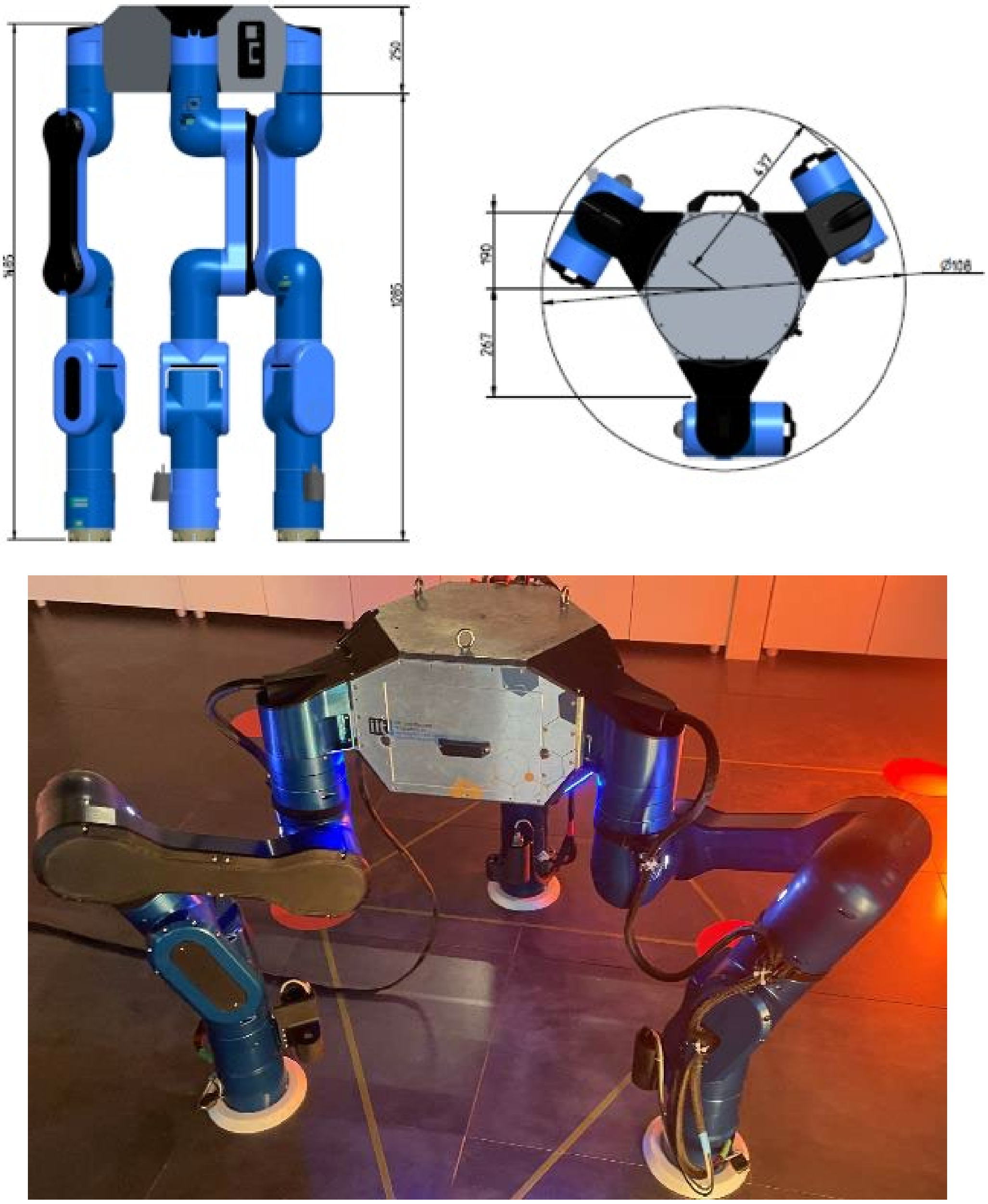


Figure 5-9: Overview of the MIRROR breadboard dimensions (top) and a vie of the complete manipulator (bottom).

5.1.1.6. ELECTRONICS BREADBOARD ARCHITECTURE

The three limbs are electrically linked to the main robot unit through several power and communication lines. To avoid ground loops to be formed during the locomotion of the breadboard platform that three limbs are electrically isolated from the main robot unit at the level of their mechanical interface with the central body. The main robot body is the house of the MIRROR breadboard RCU as well as of the EtherCAT Master Communication Unit (MCU), Figure 5-10. The RCU through a switch (D Link DSR 250N) provides a wireless communication as well as a tethered communication link to the external world, through a IP68 RJ45 port located in the central body. Through the switch the RCU has access to the perception cameras installed on the limbs, connected to the Gigagbit ports. Each arm incorporates 6 SCUs distributed along the kinematic structure and in the vicinity to the related joint actuators. The SCUs are interconnected to form an EtherCAT chain network, which is provided by a communication bus routed through the hollow shafts of the joint actuators. Each limb is terminated at the SIROM interface. The battery has integrated BMS, to simplify and lighten the central body wiring and integrate and minimize the fault causes.

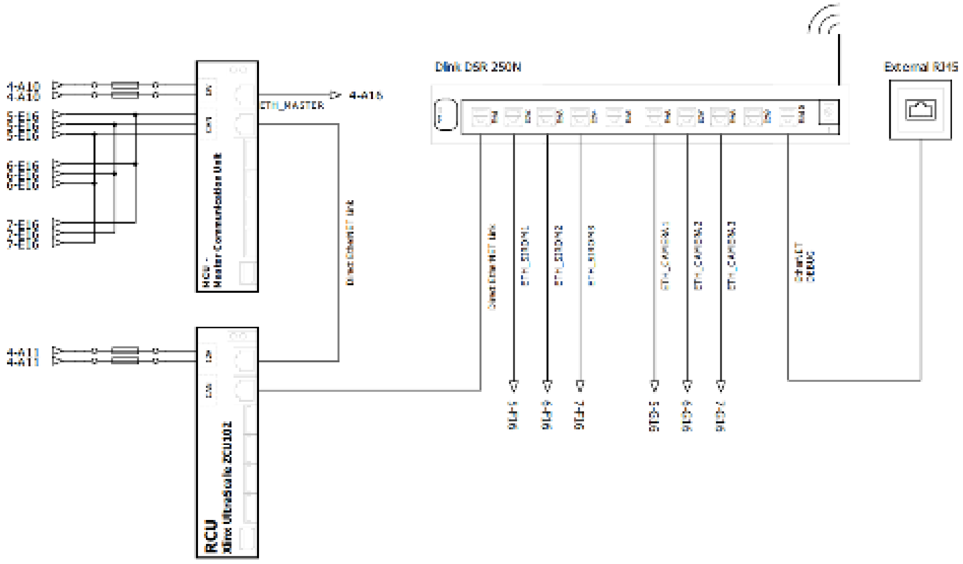


Figure 5-10: Communication architecture between the RCU, MCU and the external world.

5.1.2. SENSOR AND NAVIGATION SUBSYSTEM

The MIRROR Sensor and navigation subsystem is composed of the cameras, lighting system and fiducial markers used for precise manipulation and assembly of the structure/ORUS.

In the flight system preliminary design phase, it was decided that the cameras should be mounted on the manipulators (in eye-in-hand configuration), and not in the torso (eye-in-head), following the conclusions of a trade-off analysis. The main advantages are:

- Redundancy to loss of one camera
- Cameras can be (6D) positioned freely for best visibility
- No PTU needed
- Visual servoing is easier

In the breadboard detailed design phase, the COTS hardware for the vision system was selected:

- Camera: The model acA2040-25gm from Basler.
- Lens: V0828-MPY2 lens by Computar, with 8mm focal distance
- Lighting system: Infaimon CCS LDM2-50 selected.

Figure 5-11: Optical head (camera, lens and light) mounted on one of the manipulators

3D fiducial markers based on a combination of AprilTags installed on a 3D truncated pyramid (see Figure 5-12) were selected for SMTs precise pose estimation. It was also defined that several 3D arrangements should be imaged simultaneously to estimate the pose of a SMT with the accuracy needed for the SMT assembly. For this reason, one arrangement is installed in the corner of each SMT hexagon as shown in Figure 5-12.

Figure 5-12: 3D arrangement of AprilTag markers on SMT mock-up

5.1.3.CONTROL SUBSYSTEM

5.1.3.1. HARDWARE

During the preliminary flight design phase, it was decided that the MIRROR Control Subsystem hardware would be composed of the following components:

- A Robot Control Unit (RCU), in charge of vision processing and vision-based control, arm path planning, position and force control, FDIR, execution of OBCPs and communications.
- A number of Servo Control Units (SCUs) as needed to perform servo control of the joints. They communicate via CAN bus with the RCU.

For the MIRROR Flight system, a RCU based on the DAHLIA H2020 & NG-Ultra platforms is proposed.

For the breadboard system the Xilinx Zynq UltraScale+ MPSoC ZCU102 is the selected item to implement the high-level controller in the RCU. Also, an EtherCat Master coordinating al the SCUs, implementing real time control and communication functions and providing a single interface for the RCU was added to the design.

Note that final MIRROR tests had to be executed using a PC platform (the Control Station PC) instead of the Xilinx board due to a failure of the Xilinx and logistic problems which prevented replacing it on time.

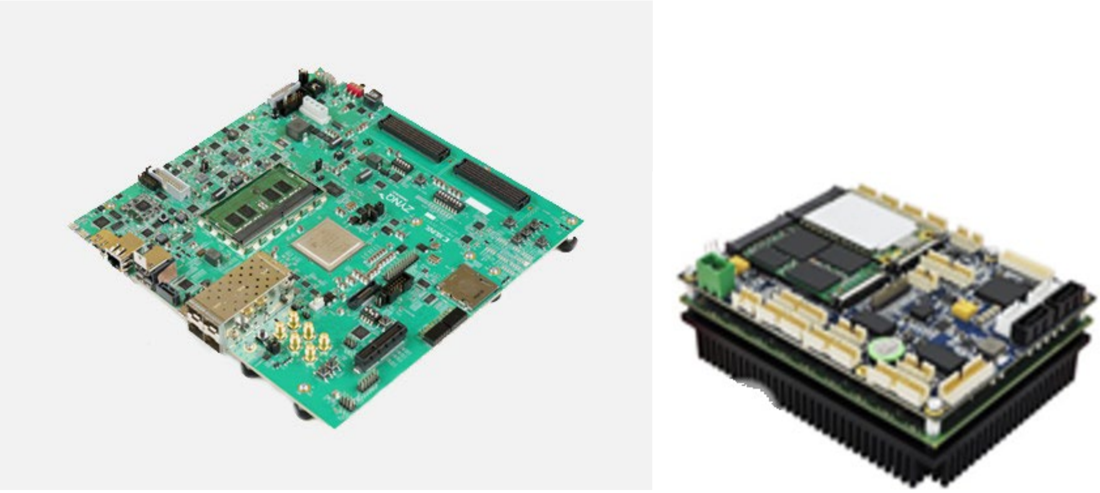


Figure 5-13. Zynq UltraScale+ MPSoC (left) and EtherCat Master (right)

5.1.3.2. SOFTWARE AND ALGORITHMS

The MIRROR control software is based on the use of the ESROCOS framework. MIRROR is based on several components of the ESROCOS framework.

The following bullets describe the software components of the MIRROR Control System:

- **GCI**: Ground Control Interface. Its purpose is to execute and monitor the telecommands received from SC/Ground, generating telemetry, and managing the execution of the rest of the components.
- **RMMP**: Relocatable Manipulator Motion Planner. It is responsible for determining the end effector poses for each operation, generating collision free trajectories and using visual and force/torque feedback.
- **FDIR**: Failure Detection Isolation and Recovery. Its purpose is to detect all failures with the potential to cause loss of function/mission, and to allow the required recovery action.
- **OBCPL**: On-Board Control Procedure Library. The OBCPL component purpose is to execute autonomously Flight Control Procedures encoded as OBCPs.

Two types of Image Based Visual Servoing algorithms were implemented for manipulating and assembling the structural/payload elements:

- **Eye-in-hand Visual Servoing**: Used mainly for the Manipulator Attach operation and using for feedback the camera on the arm that is being controlled.

- **Eye-in-head (external) Visual Servoing**: Used mainly for the SMT Assembly operation and using for feedback the camera on an arm different that the one that is being controlled.

Impedance control is implemented to avoid exerting high forces on the structure as well as to allow SIROM latching. In addition, a gravity compensation term is used to allow ground testing under 1-G.

5.1.4. SYSTEM INTERCONNECT

SIROM (Standard Interface for Robotic Manipulation) is a robotic interface integrating mechanical, data, power, and thermal coupling in a single and compact electro-mechanism. As a standard interface, SIROM allows the coupling of payloads-to-manipulators, payloads-to-payloads, as well as payloads-to-spacecraft.

In MIRROR, SIROMs are used as manipulator end effectors for manipulation and locomotion. They are also installed in the telescope mock-ups used to test the breadboard robot, both of robot manipulation and for tile-to-tile assembly.

SIROM 2.0 is the baseline solution implemented in H2020 EROSS (European Robotic Orbital Support Services) to be used for ORU (Orbital Replacement Unit) transfer in an on-orbit servicing mission. In MIRROR, a modified version of SIROM 2.0 was adapted to the specific project requirements for the assembly of hexagonal mirror tiles to form a large structure. Here, stringent requirements related to triple docking have led to the modification of the external guiding petals.

5.1.4.1. GENERAL DESCRIPTION

SIROM design is a 4-in1 integrated interface combining mechanical, data, electrical and thermal connectivity in a single envelope.

- The mechanical interface allows coupling of payload modules providing a robust and reliable connection
- The electrical interface allows bi-directional power transfer between mated SIROM pairs.
- The data interface enables telemetry (TM), telecommands (TC) as well as high speed data transmission
- Thermally, mated SIROMs allow heat transmission through their heat conductive (aluminum) contact areas.

In achieving its functionality, the system encompasses the following main elements:

- The SIROM Mechanism – Hosts the respective mechanisms the respective sensors position.
- The SIROM Connectors plate – PCB consisting of pogo pins & pads that allow establishing data and electrical continuity between mated SIs.
- The SIROM Electronics – It oversees control and power of the SIROM mechanism, encompassing the communications links and providing direct sensors acquisitions and housekeeping data.
- Harness.
- External rear connectors.

The following figure shows a view of the design solution encompassing the above-mentioned main elements adapted for MIRROR project.

5.1.4.2. SIROM VERSIONS

For MIRROR, it is proposed using two different SIROM versions to save total mass and volume. These versions are the following:

1. Full Active: Contains all mechanical elements and electronics
2. Passive: Does not include latching system, actuator (i.e., no elements involved in the motion transmission), nor the electronics. It does include the Connectors PCB to allow data and electrical transfer between SIROMs and rear connectors at its bottom side.

The mass for each version is:

- Active: 1,14kg
- Passive: 0,42kg

The following figures show several views of the two versions.

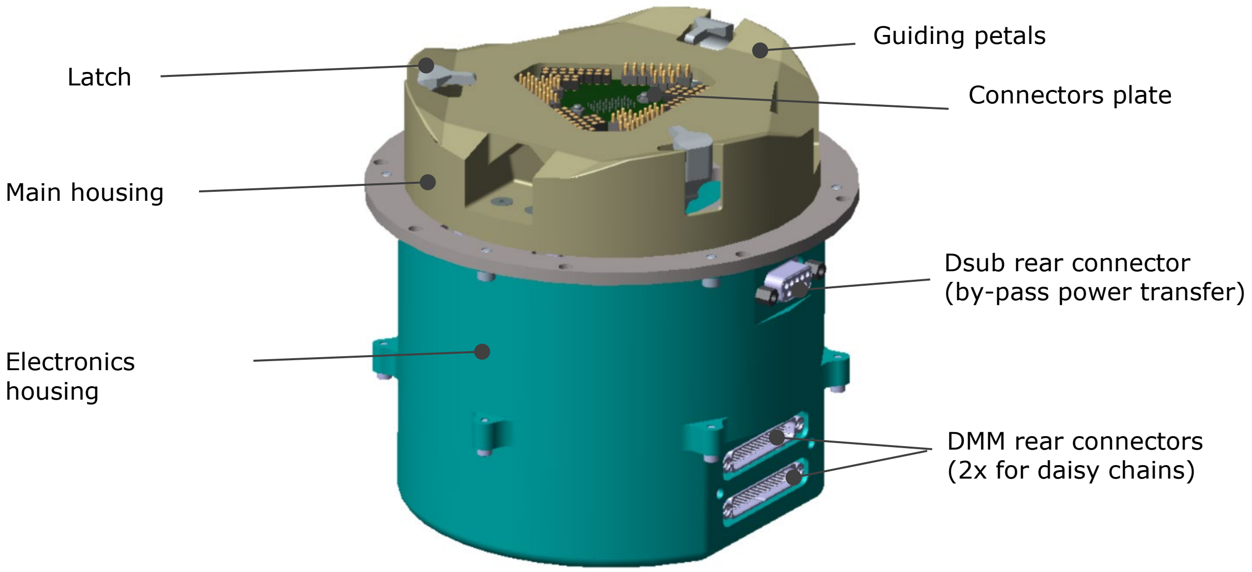


Figure 5-14 Active SIROM – front view

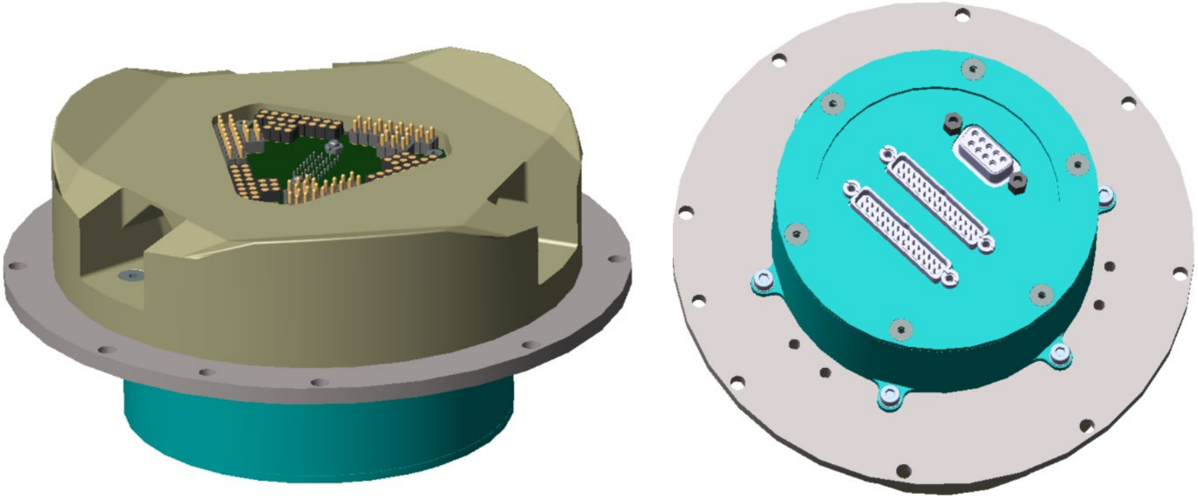


Figure 5-15: Passive SIROM – front and bottom views

5.2. TESTBED

The MIRROR Testbed system is composed of the following subsystems:

- Single Mirror Tile Mock-up (SMTMU): The SMT Mock-up is the simulated SMT that is manipulated by the MIRROR breadboard robot during the tests.
- Telescope Spacecraft Mock-Up (SCMU): The Telescope Spacecraft Mock-up (SCMU) simulates the structure that the MIRROR system is assembling.
- Weight Compensation Device (WCD): The Weight Compensation Device (WCD) is composed of counterweights and an industrial manipulator which is used to apply the compensating force of the counterweights exactly over the attachment point to the SCMU.
- Fixed structures (Manipulator Robot Stand and Storage Area). Structural elements used to support the robot and an SMT.
- Safety Devices (Barriers and switches).

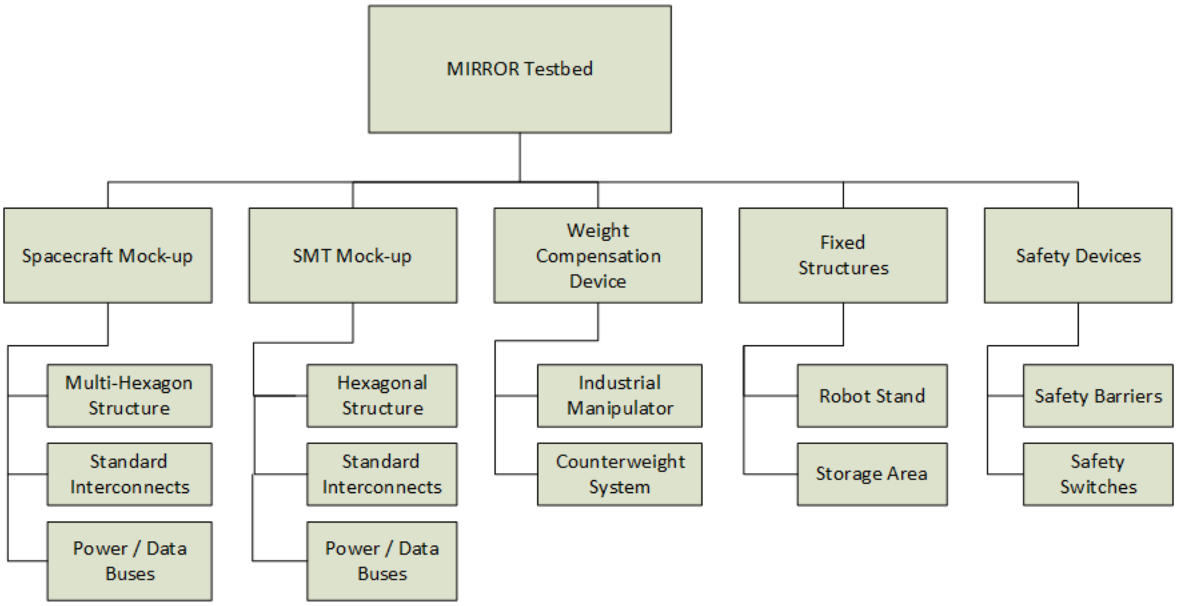


Figure 5-16: MIRROR testbed product tree

The following figures identify the main testbed parts.

Figure 5-17.: SMT implementation.

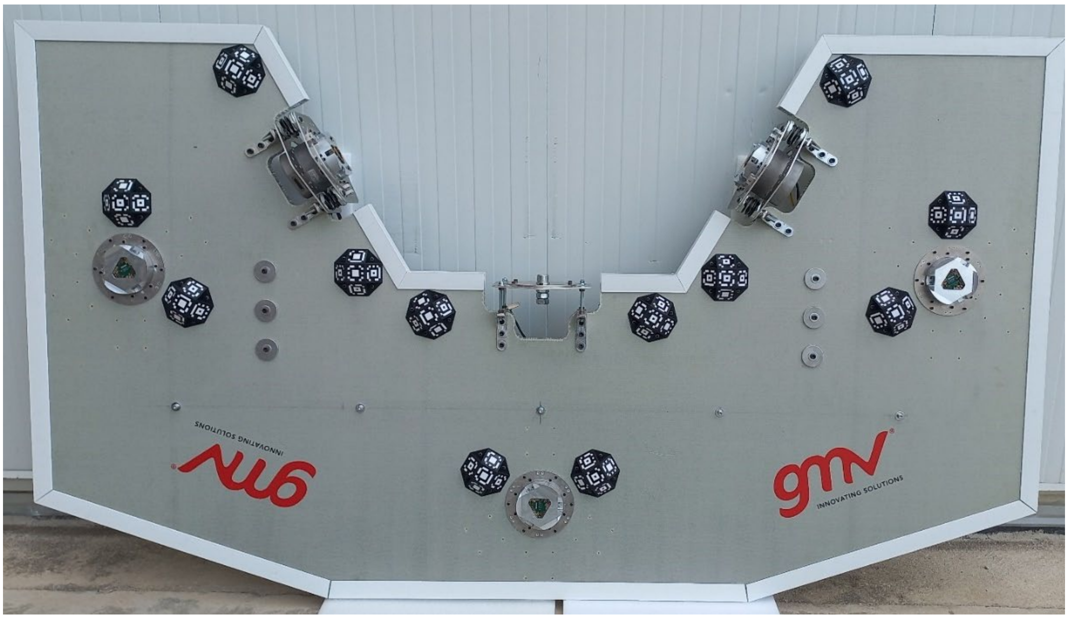


Figure 5-18. SCMU implementation.

Figure 5-19 Robot installed on the stand and storage area (with SMT).

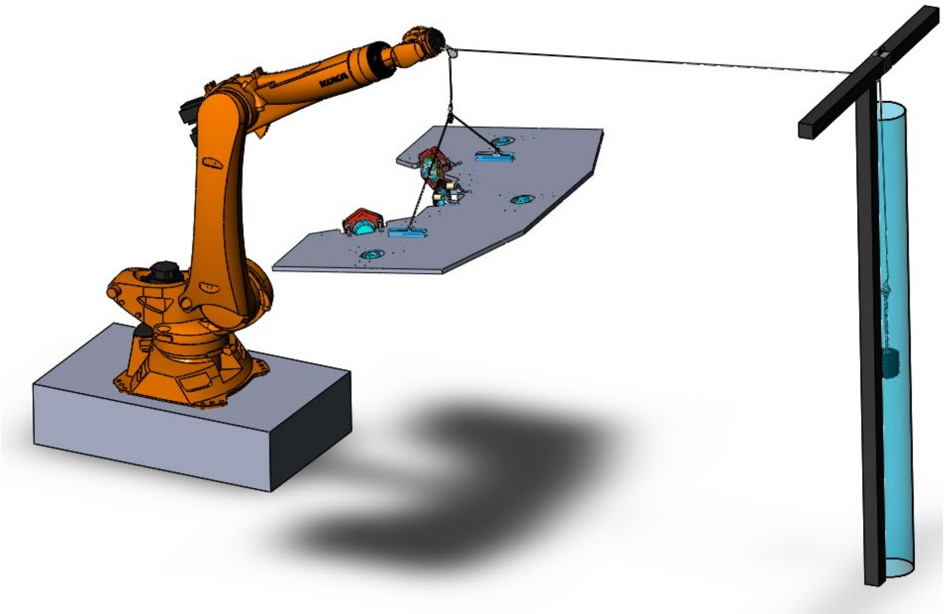


Figure 5-20 WCD design (with SCMU).

Also, a Control Station is used for controlling the testbed and the breadboard robot. The testbed controller is used for:

- Control/Monitoring of the breadboard system.
- Control/Monitoring of the testbed.
- User Interface.

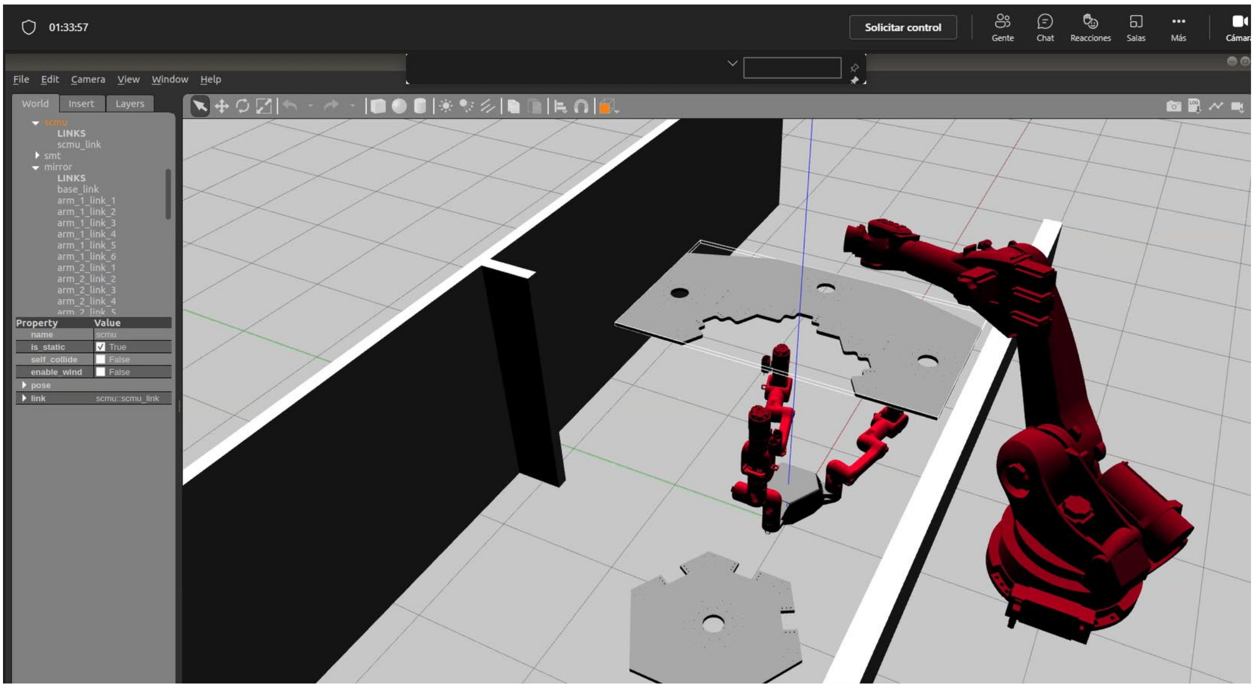
An x86 computer running a Linux Ubuntu operating system is selected to implement the testbed.

6. SIMULATOR

A kinematic simulator has been developed in MIRROR for demonstrating the high-level operations as specified in the Concept of Operations [RD.1]. The simulations are not intended to replicate low-level control or low-level physical interactions, but to show that the robot kinematics allow completing the defined mission, and particularly the main basic operations such as locomotion or assembly.

The MIRROR Simulator, based on Gazebo, replicates both kinematically and visually the breadboard robot and the testbed mock-ups used to validate it. It also replicates the industrial manipulator (Kuka) used to implement the Weight compensation Device.

The simulator implements communication interfaces to the MIRROR High-level control Software. This allows testing the software itself, as well as designing the robot operations and tests in an efficient and straightforward way.



Property	Value
name	scmu
is_static	☑ True
self_collide	☐ False
enable_wind	☐ False
pose	
link	scmu::scmu_link

Figure 6-1 MIRROR Simulator

7. TESTING

7.1. TEST PLAN

The validation of the MIRROR breadboard follows an iterative and incremental approach, including:

- Early assessments/evaluation of technologies.
- Subsystem testing.
- Integration testing.
- System testing.

System tests are performed with the MIRROR breadboard and testbed in the test facility, and are aimed at demonstrating the functionality, performances and robustness of the overall MIRROR system in laboratory conditions.

The tests focus on a subset of the system and subsystem requirements as specified in the System Requirements Document [RD.2].

The validation approach at system level is based on:

- Validation of the MIRROR main basic operations in a realistic physical environment, implemented by the testbed composed of mock-ups of the SMTs and spacecraft structure, and a weight compensation device, simulating the Zero-G conditions.
  The main operations validated in the physical environment are:
    - Manipulator Attachment / Manipulator Detachment
    - Locomotion
    - SMT/ORU Assembly / Disassembly (Simple, Double and Triple)
    - Deployment and checkout /Stowage
- Validation at system level in simulated environment.

7.2. SYSTEM TEST RESULTS

7.2.1. LOCOMOTION

In the locomotion test the breadboard robot walks on the manipulation SIROMs of the telescope mock-up (SCMU). The tests were executed in controlled light conditions, with focused light from the vision heads (MIRROR lights) and diffuse ambient light. The weight compensation device was used to offload the telescope mock-up.

The locomotion tests were executed successfully. The test itself implied the execution of 6 walking steps on the telescope mock-up. In addition, the test was repeated 5 times to ensure consistency. Furthermore, several dry runs were executed, adding up tens of executions. In all these executions the system showed **very high reliability**, without any remarkable failure:

- The eye-in-hand visual servoing algorithms showed enough precision in all cases for attaching a single SIROM interface.
- The impedance control resulted in a compliant enough behaviour for allowing the latching of the SIROMs in all cases.
- Interaction with the weight compensation device proved not to be a problem (no stability problems observed).

Figure 7-1 System locomotion test

7.2.2. SMT ASSEMBLY

In the assembly tests the breadboard robot assembles a SMT to the telescope mock-up (SCMU). As in the previous case, the tests were executed in controlled light conditions, with focused light from the vision heads (MIRROR lights) and diffuse ambient light. The weight compensation device was used to offload the telescope mock-up.

Single, double, and triple assembly tests were executed successfully up to 5 times, showing **good reliability in controlled conditions**:

- The eye-in-head (external) visual servoing algorithms showed enough precision for assembling the SMT in all cases.
- The impedance control resulted in a compliant enough behaviour for allowing the latching of the assembly SIROMs, although in some cases the SIROMs reported that the electric connection could not be established.
- Triple assembly imposes a tight trajectory to reach the capture volumes of the three SIROMs. The use of combined impedance control and visual servoing is recommended for safety reasons, although with an accurate enough control it is not mandatory.

Figure 7-2 System assembly test

7.2.3. VISION ROBUSTNESS TEST

In the vision robustness test, triple assembly and disassembly operations were executed 5 times, with the following lighting conditions:

- Darkness (only the manipulator lights were used)
- Focused light near the telescope plane (in addition to manipulator lights)

All tests were executed successfully, with the following comments:

- Exposure time was adjusted manually for each case, but no changes were needed during the test. Autoexposure and HDR algorithms (not tested in the breadboard) will be needed in a future flight system.
- Failure to establish connection on the SIROMS (as in the assembly tests) were detected, although this does not affect the main result of the test, which focuses on vision robustness.

Figure 7-3 System vision robustness test in darkness

7.2.4. STRUCTURE MISALIGNMENT TEST

In this test, triple assembly and disassembly operations are executed 5 times, with the following misalignment conditions in one of the three assembly SIROMs of the telescope mock-up:

- 0 mm misalignment
- 2 mm misalignment

In the telescope mock-up, only two of the three assembly SIROMs were mounted on elastic couplings, while no couplings were used in the SMT mock-up. These couplings are intended to provide some degree of accommodation to alleviate the misalignments of the testbed.

The test was only successful for misalignment errors of less than 2mm. It was found that small misalignments prevented a correct latching of the SIROMs. The failure to complete the latching could be mitigated if all the assembly SIROMs were mounted 6DOF elastic couplings (at least on SIROM in each pair). The use of these couplings in the structure is recommended.

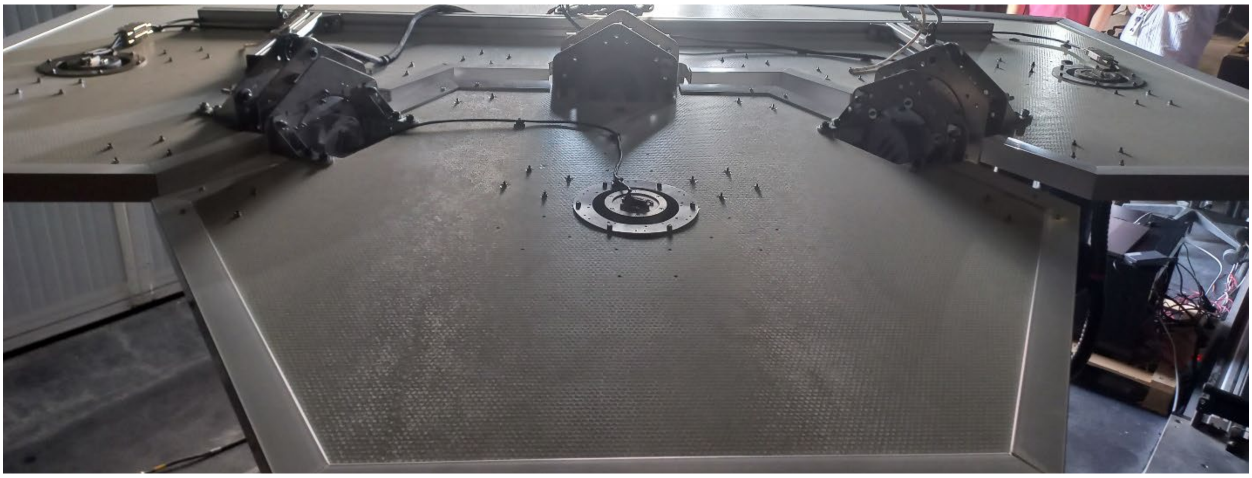


Figure 7-4 Upper view of telescope and SMT mock-ups during an assembly operation.

8. LESSONS LEARNT

This section summarizes the lessons learnt during the development and testing of the MIRROR system:

- The selected camera configuration (one camera and light mounted near each of the three end-effectors) is recommended for maximum visibility, accuracy, and redundancy.
- The vision system must be reassessed and tested in representative lighting conditions (intense sunlight representative of in-orbit illumination). Camera autoexposure and HDR should be implemented in next evolutions. Lighting system power should be reassessed as well to be effectively used as fill light in scenarios partially illuminated by the sun.
- Smaller 3D markers could be used for SMT attach operations. Simpler 2D markers could be used for SMT assembly, if they are conveniently distributed along the SMT. This reassessment would relax the requirements imposed to SMT design, with smaller and less bulky fiducials.
- An intermediate processor between the RCU (running high-level algorithms such as vision) and the SCUs (running low-level servo control) providing a centralised interface to SCUs and implementing real time and communication operations has proved to be a good choice. This intermediate control level was implemented by the EtherCat Master in the breadboard system and a similar approach is recommended for a flight system.
- The use of compliant couplings between the assembly SIROMs and the structure is recommended to provide some degree of accommodation to cope with structure mounting misalignments, in case the structure is not accurately built. This does not apply to space qualified structures built with high precision.
- Visual-based control approach has been validated (in controlled light conditions) for complex assembly operations. It is accurate enough to complete triple assembly operations (2mm, 0.5 degrees accuracy needed), stable even in the presence of vibrations and robust to lighting conditions (in laboratory).
- Soft collisions can be expected during assembly operations, particularly in triple assemblies, but they are not problematic. The use of impedance control combined with visual servoing for the last approach motion is recommended for safety reasons.
- OBCPs have resulted a very convenient, flexible way for defining tests and, generally, for defining automated but flexible operations.
- The weight compensation device has worked as expected and has not interfered in the tests. With some minor improvements, the proposed design is recommended for ground testing of in-orbit servicing applications.

9. CONCLUSIONS

The development and testing of the MIRROR system has demonstrated the feasibility of the multi-arm re-locatable manipulator concept for in-orbit servicing. The essential operations required for the assembly of an arbitrarily large structure in orbit, specifically locomotion and assembly, have been successfully proven on the ground in a specific use case, the assembly of a tiled telescope reflector. Moreover, the proposed operational strategy and design for both the flight system and the breadboard have been verified as a practical solution for in-orbit servicing broadly, encompassing, but not limited to, spacecraft reconfiguration, as well as structure assembly, maintenance, and decommissioning. The MIRROR system development has considered the diverse range of tasks it could potentially undertake in the future. As a result, its design remains as universal as possible, enabling easy adaptation to any type of in-orbit servicing mission. The insights gained during this process establish a path for refining the system and progressing towards a potential flight system.

For the SENER team, the involvement in the MIRROR project has been very successful, in terms of the achievements and also as a learning experience for future in-space assembly applications. The SIROM interface has been updated to adapt to the constraints of the project. These upgrades will be integrated in future versions since they have been validated within this project. Also, the involvement with GMV through the MAIT activities, supporting the team when needed, have given the SENER team valuable insight into the most common issues when operating our SIs. The lessons that were extracted will be incorporated into our designs to provide an easier integration process in future projects.

END OF DOCUMENT