Final Presentation to ESA

MIRROR:
A RE-LOCATABLE MANIPULATOR FOR ON-ORBIT ASSEMBLY AND SERVICING

Multi-arm Installation Robot for Readying ORUS and Reflectors

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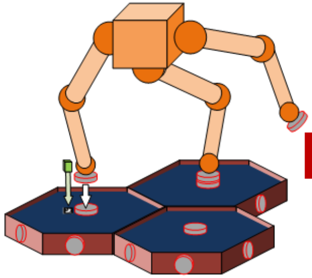
gmv INNOVATING SOLUTIONS

Introduction

- **Multi-arm Installation Robot for Readying ORUS and Reflectors (MIRROR)**
- ESA contract covering preliminary design (flight system) and development and ground testing of a breadboard demonstrator (TRL4)
- Industrial Consortium:

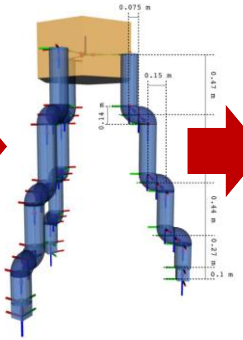
MIRROR System Development

Development process



Requirements & CONOPS

SRR June 2020

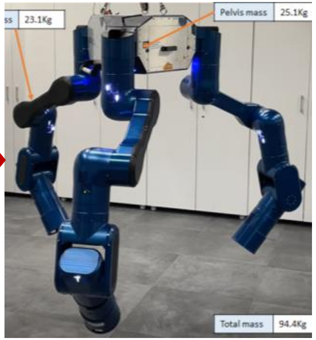


Preliminary Design of Flight System

PDR Nov 2020

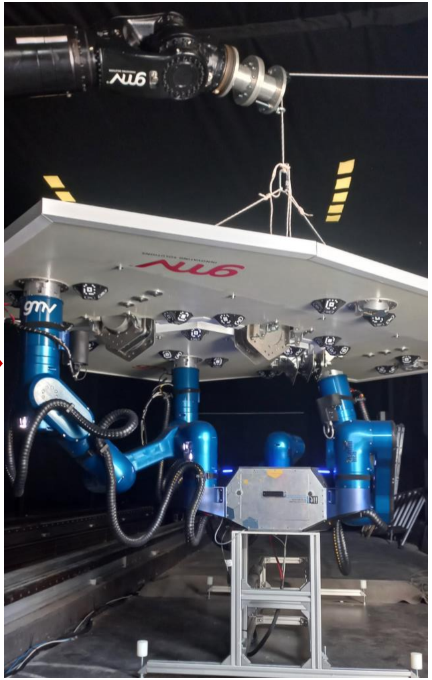
Detailed Design of Breadboard System

BDR April 2021



Manufacturing and Integration

TRR July 2022



Ground testing of Breadboard System

FA July 2023

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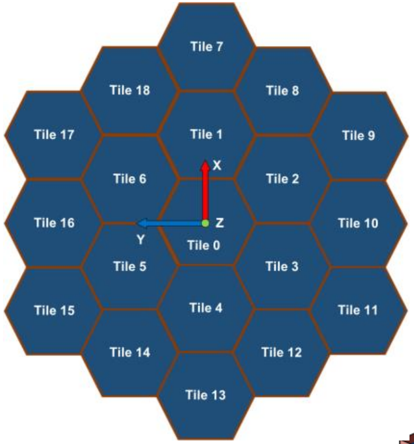
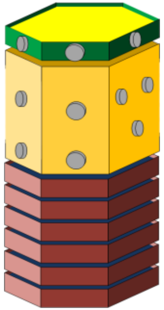
Mission and Concept of Operation (I)

Scenario

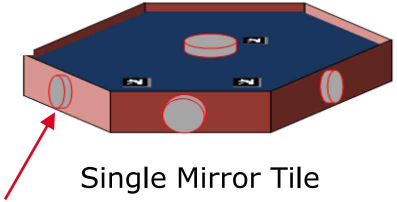
On-orbit Assembly of a Multi-Ring Telescope Reflector



Tiled Reflector



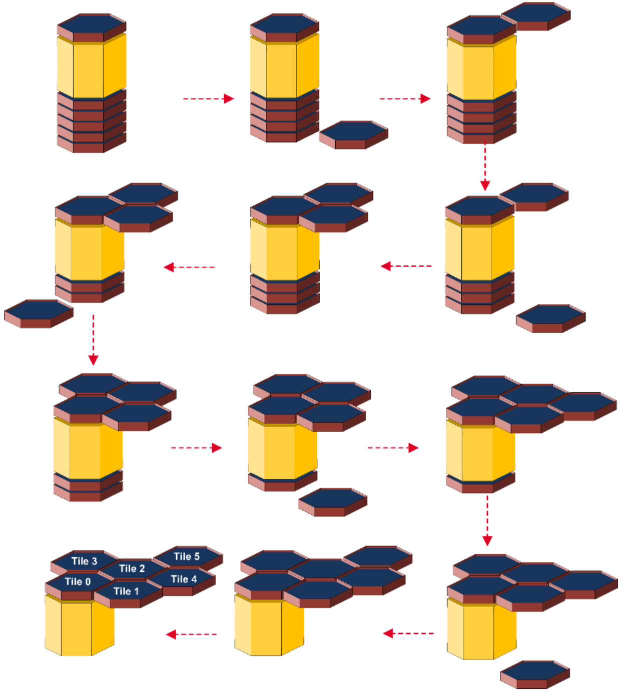
Telescope Spacecraft



Single Mirror Tile

Standard Interconnects

Launch Configuration

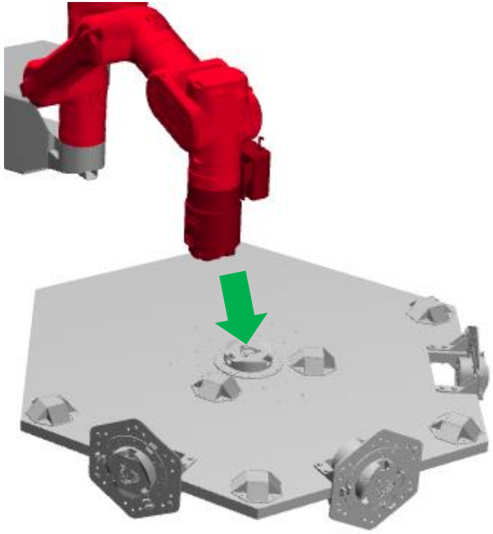


On Orbit Assembly

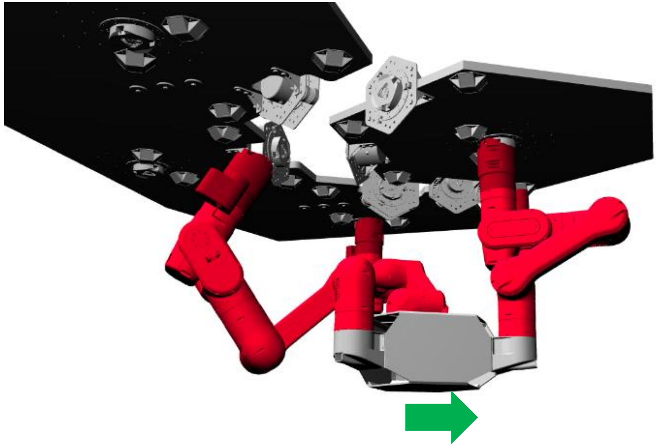
Mission and Concept of Operation (II)

Concept of Operation

Multi-Arm Relocatable Manipulator equipped with **three arms** capable of three main operations:

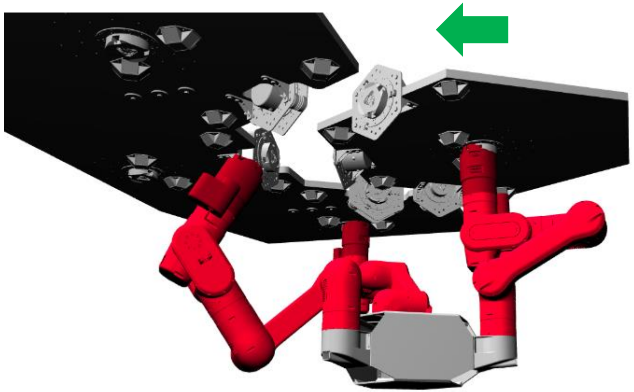


Tile Manipulation



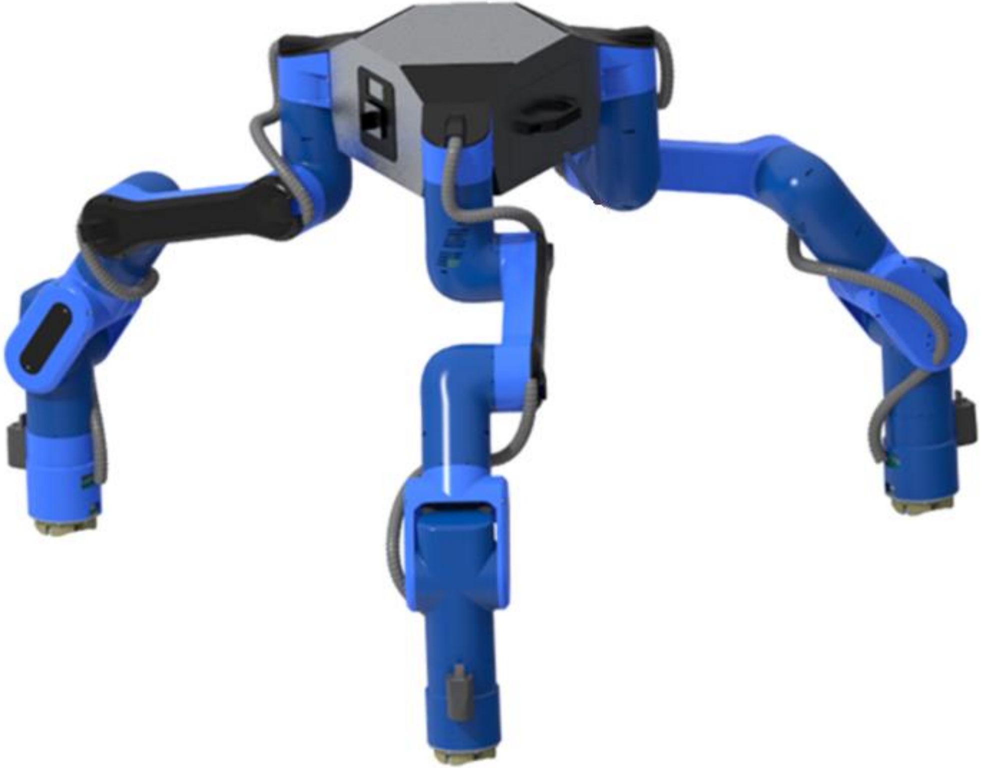
Locomotion & Tile Transport

Walk with two arms, eventually use the third one to transport a tile



Tile assembly

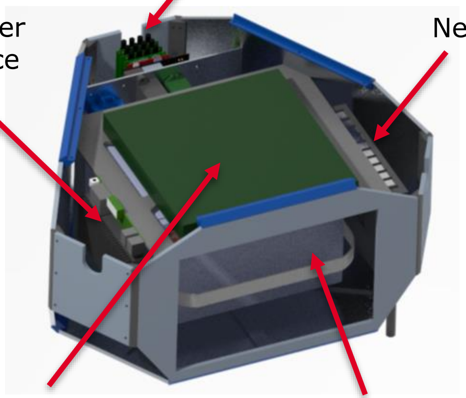
Contents

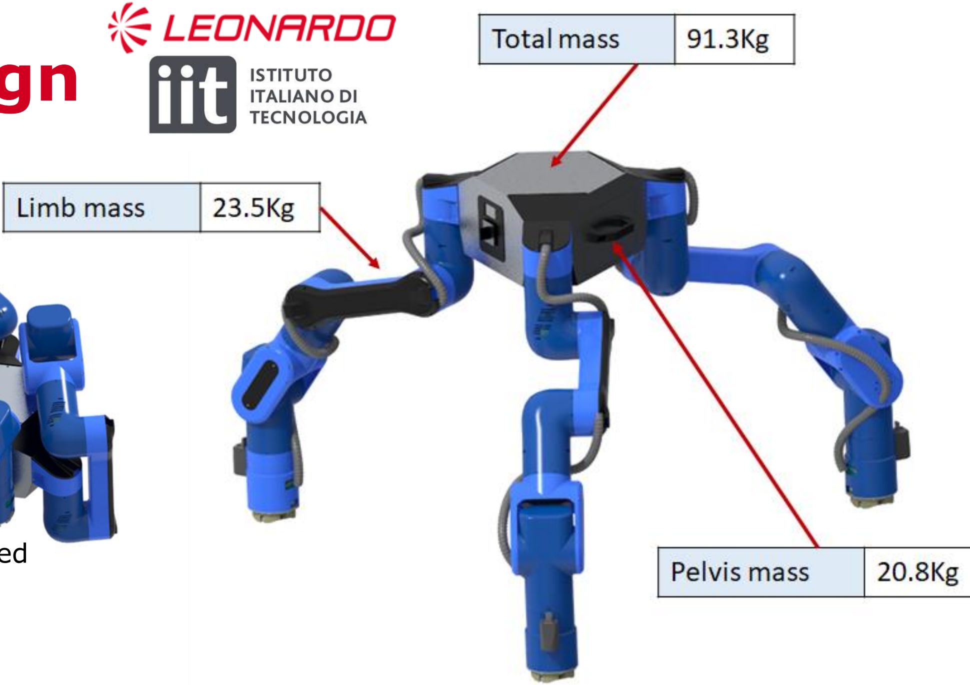


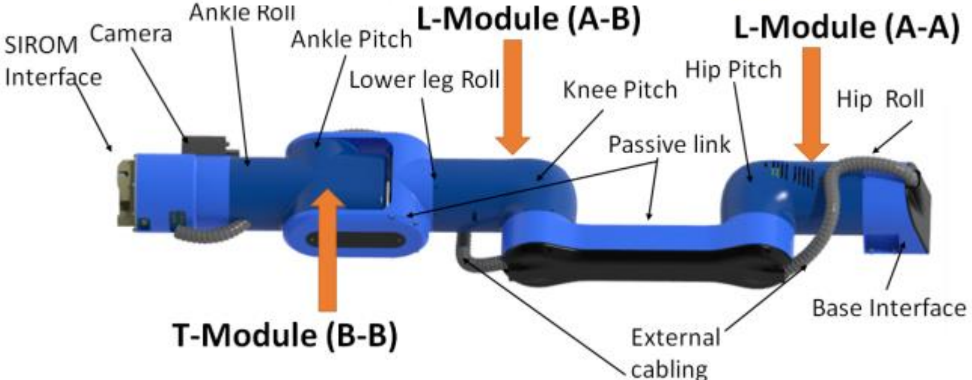
Breadboard System Design

Relocatable Manipulator

- Exoskeleton structure including:
  - Pelvis
  - Three identical 6DOF arms
  - End effectors → SIROM



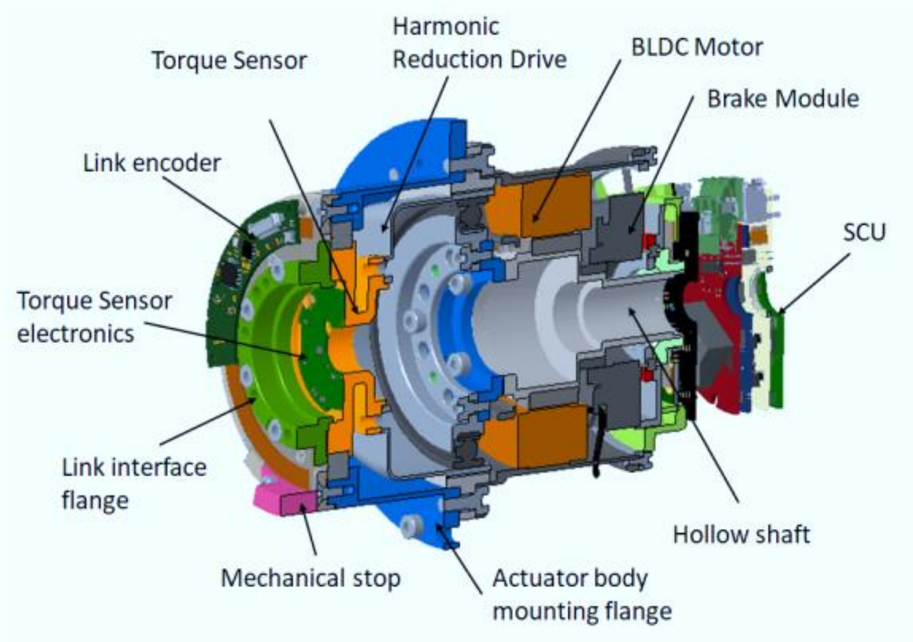


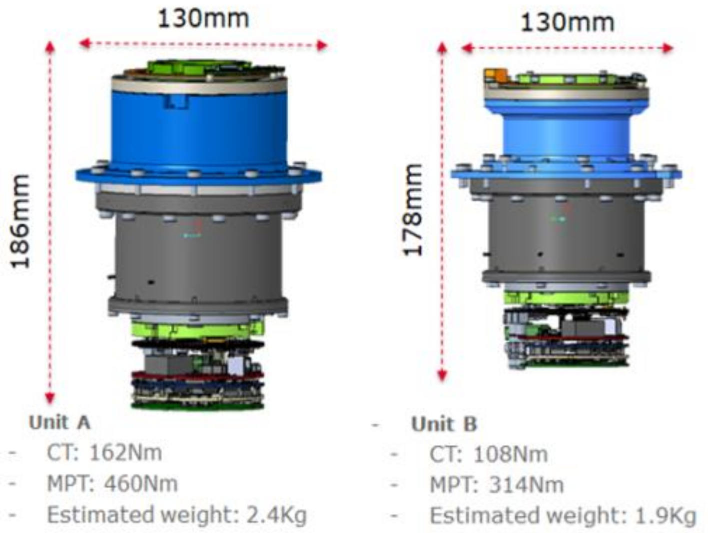


Breadboard System Design

Relocatable Manipulator

- Manipulator based on two actuator set sizes →





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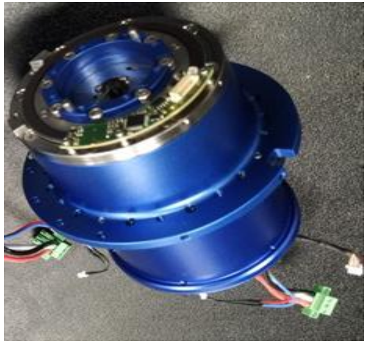
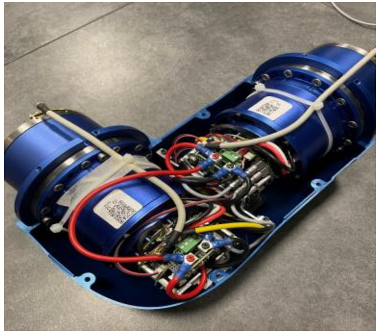
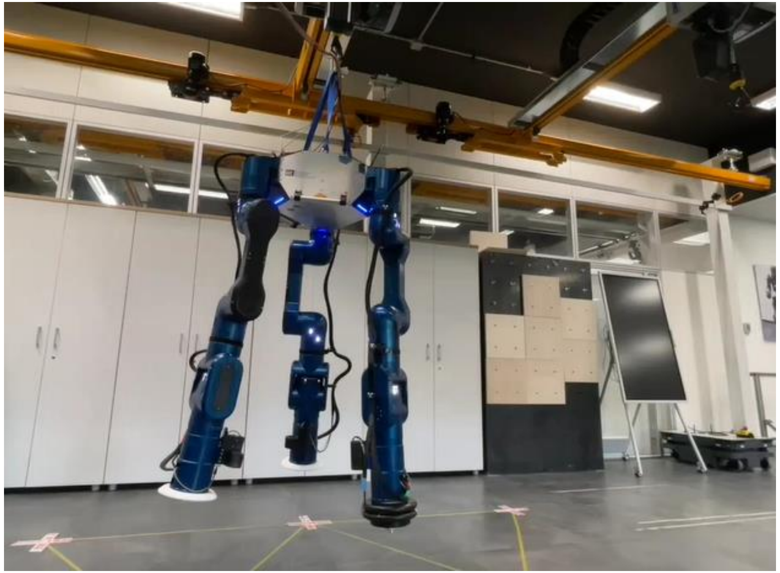
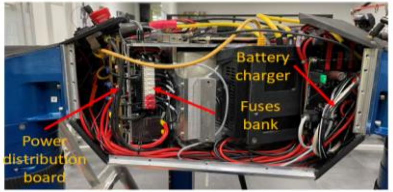
Breadboard System Design

Relocatable Manipulator









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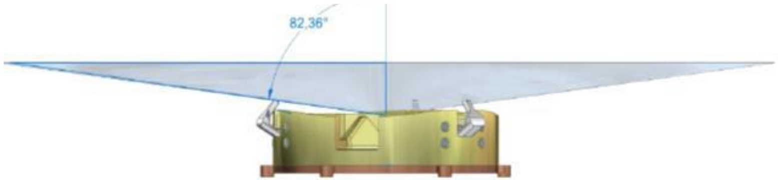
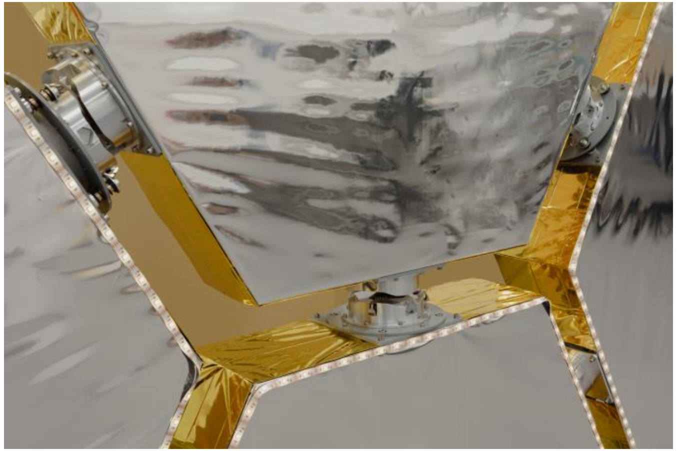
Breadboard System Design

Standard Interconnect (SIROM)

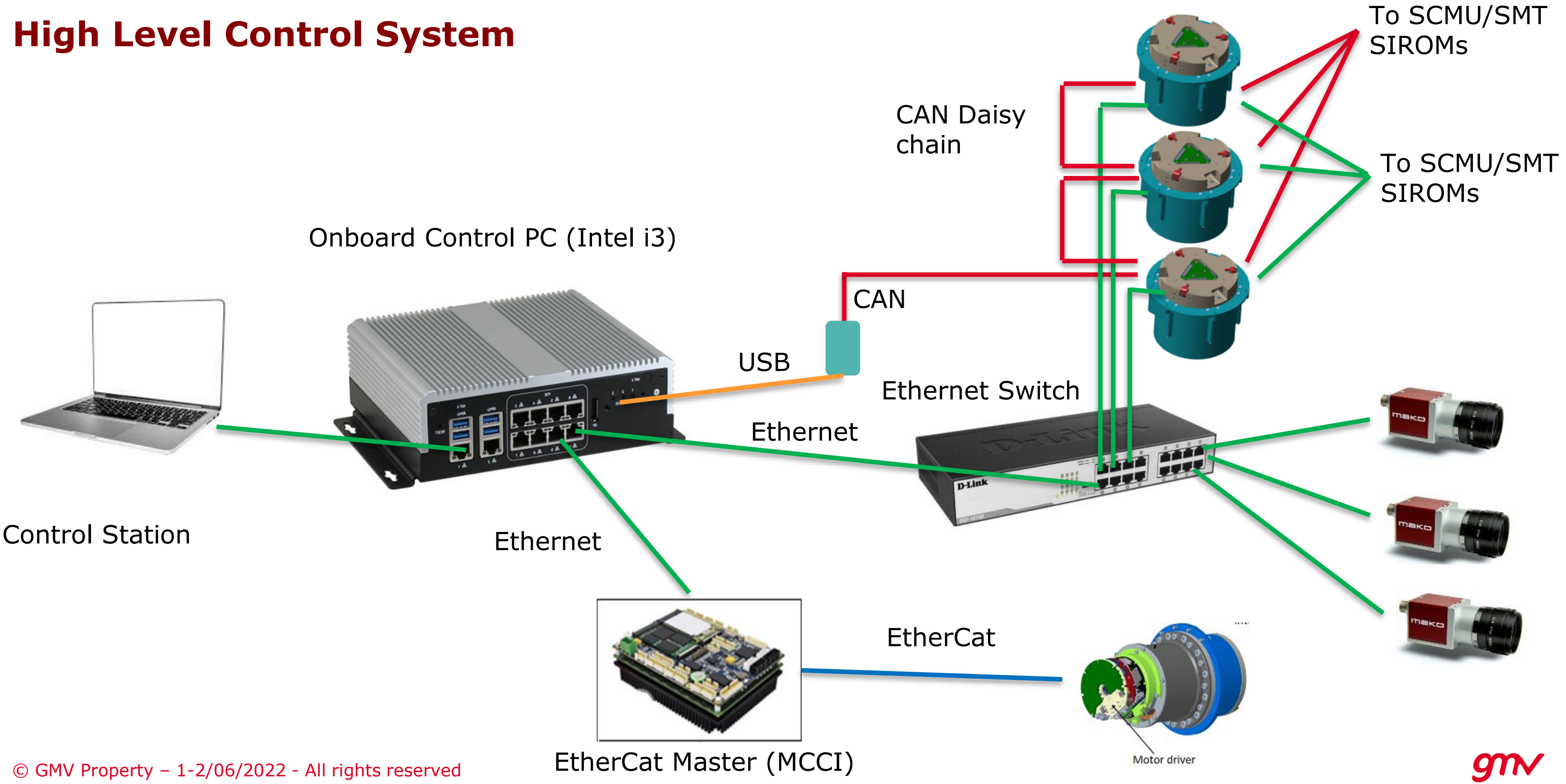
- SIROM (Standard Interface for Robotic Manipulation)
- Integrated interface: mechanical, data, electrical and fluid connectivity
- Evolution of a TRL-6 H2020 development:
  - Guiding surfaces allowing docking with angle >60º
  - Removal of fluid interface
  - Higher deliverable latches force
  - Lines for high power transmission
  - Active and Passive versions (1,1kg and 0,43 Kg)





Breadboard System Design

High Level Control System



Breadboard System Design

Vision System

3 Cameras and ligts near end-effectors

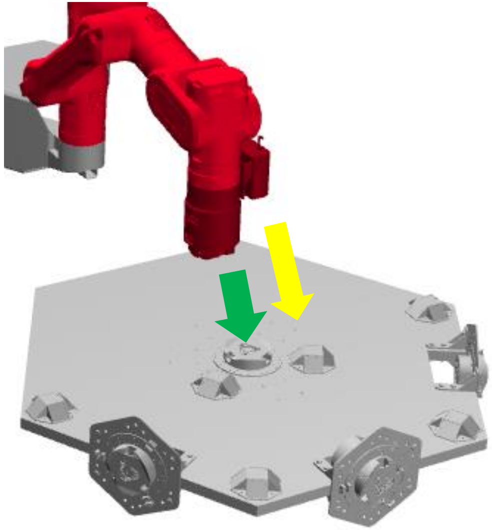
3D fiducial markers

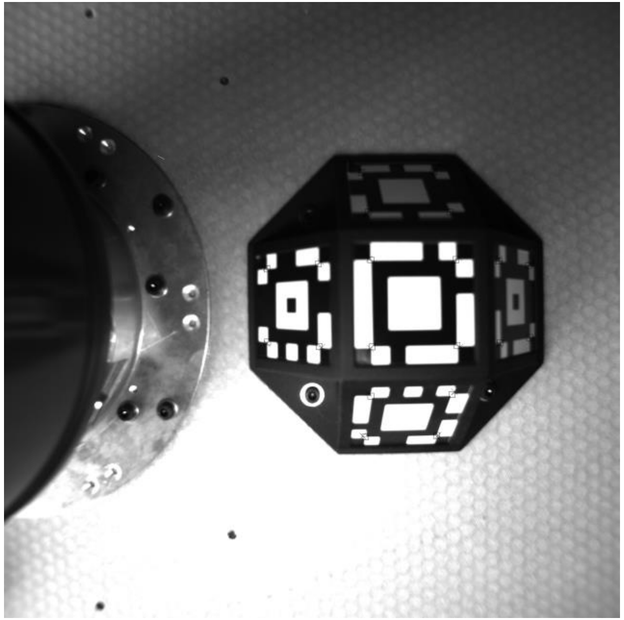
Image Based Visual Servoing:

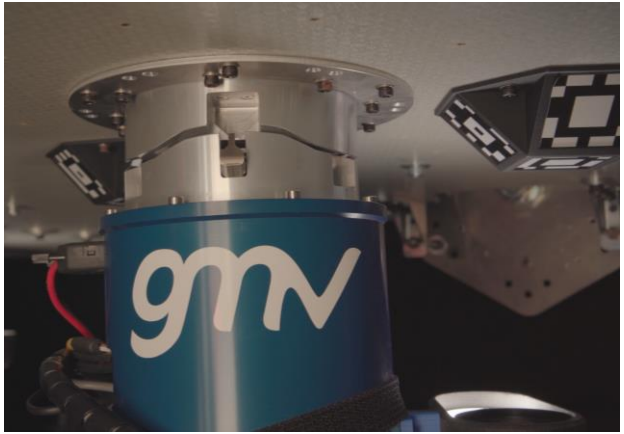
- Eye-in-hand Visual Servoing: Manipulator Attach
- Eye-in-head (external): SMT Assembly

Breadboard System Design

Visual Control: Eye-in-hand Visual Servoing

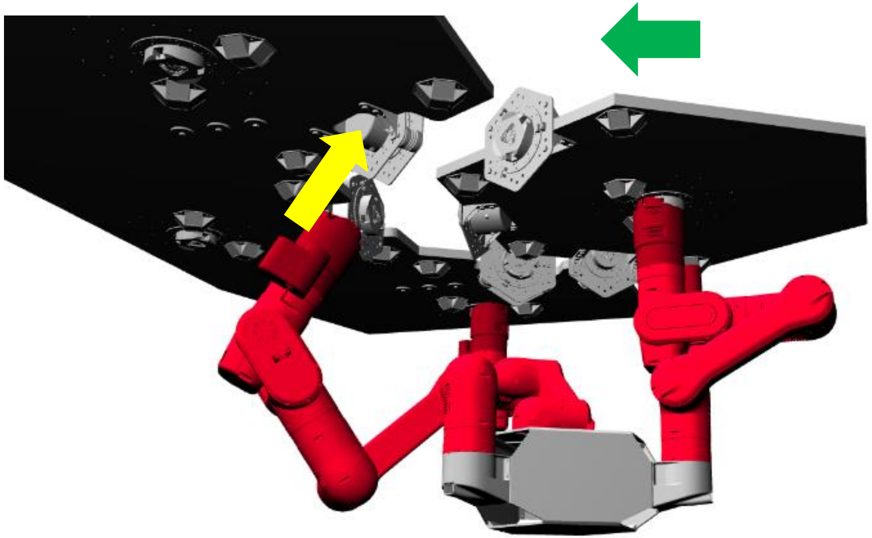


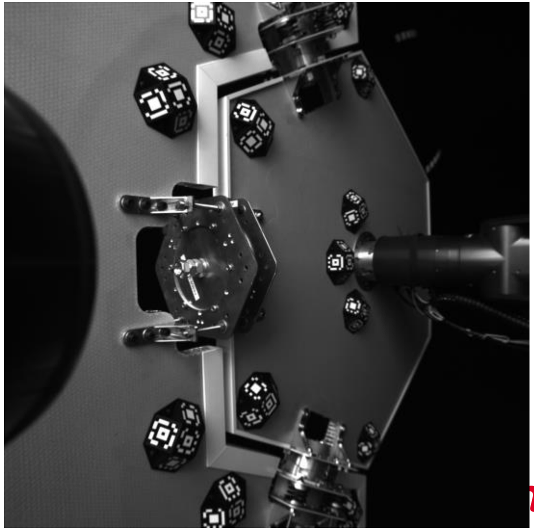




Breadboard System Design

Visual Control: External visual servoing





Breadboard System Design

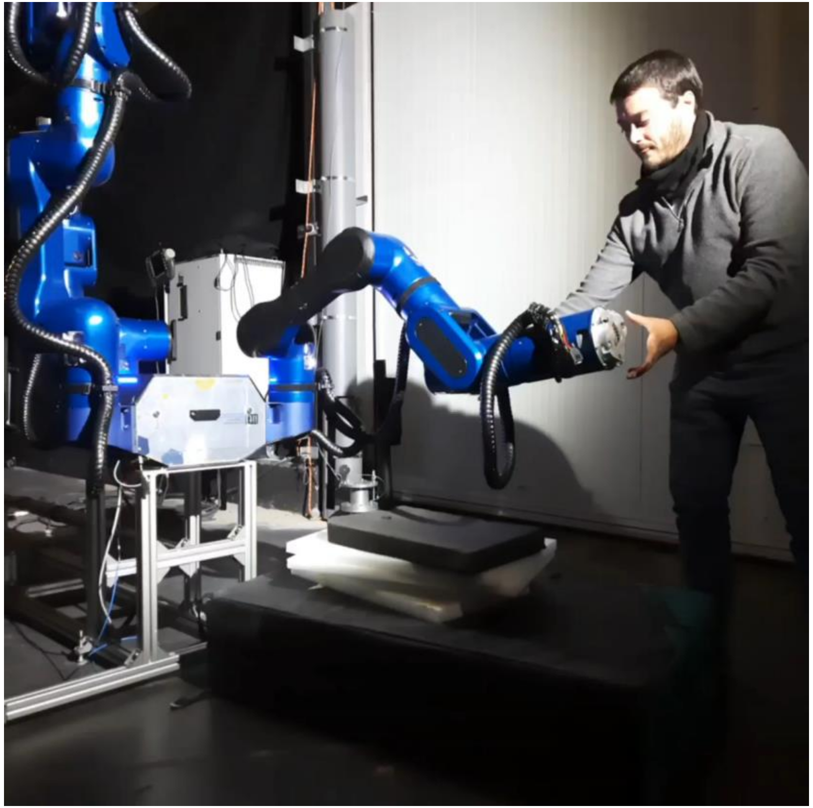
Force-based Control

Impedance Control (IC)

Gravity compensation used for ground testing

Two IC use cases:

- Safe Visual approach for SMT Assembly and Manipulator Attach
- Force relaxation for SIROM latching



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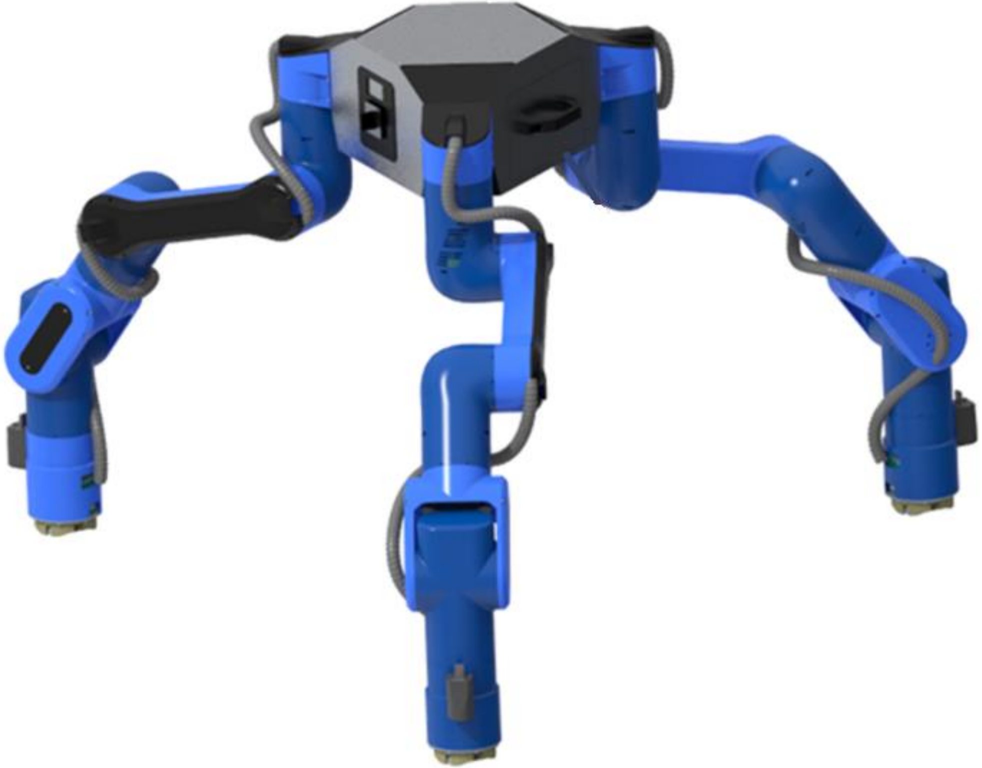
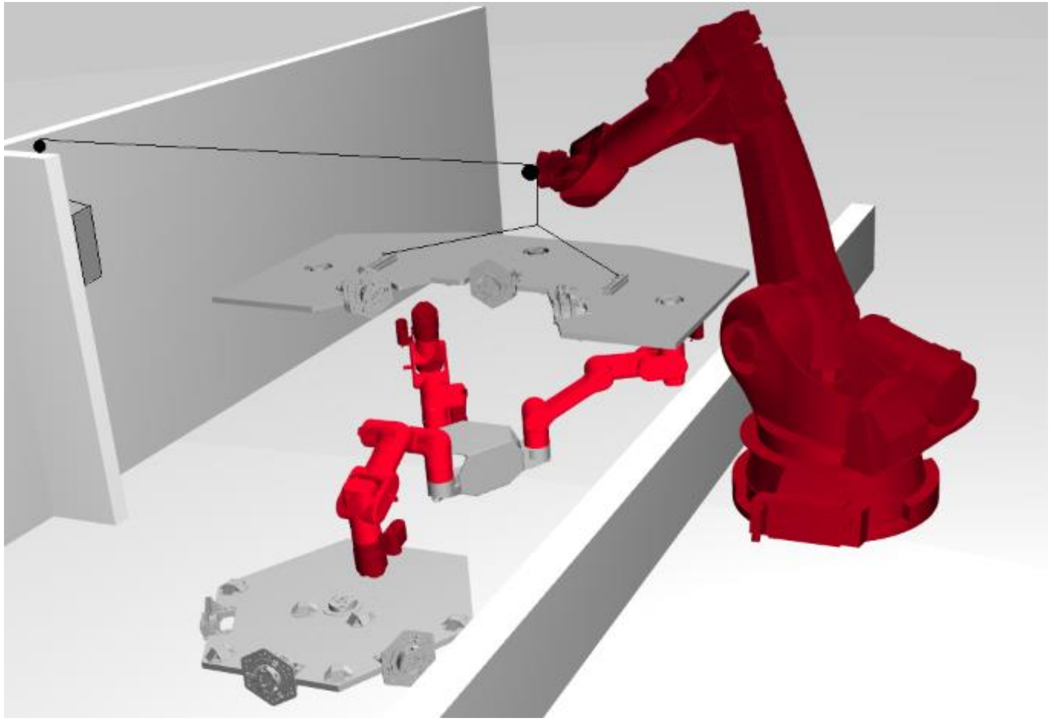
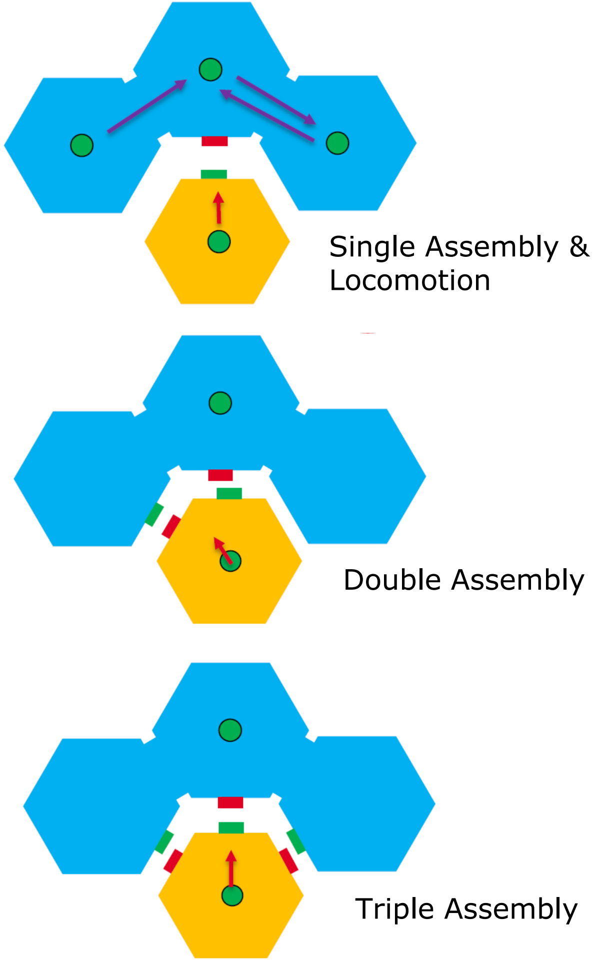


Test Plan

Ground Test Setup and main operations to be tested



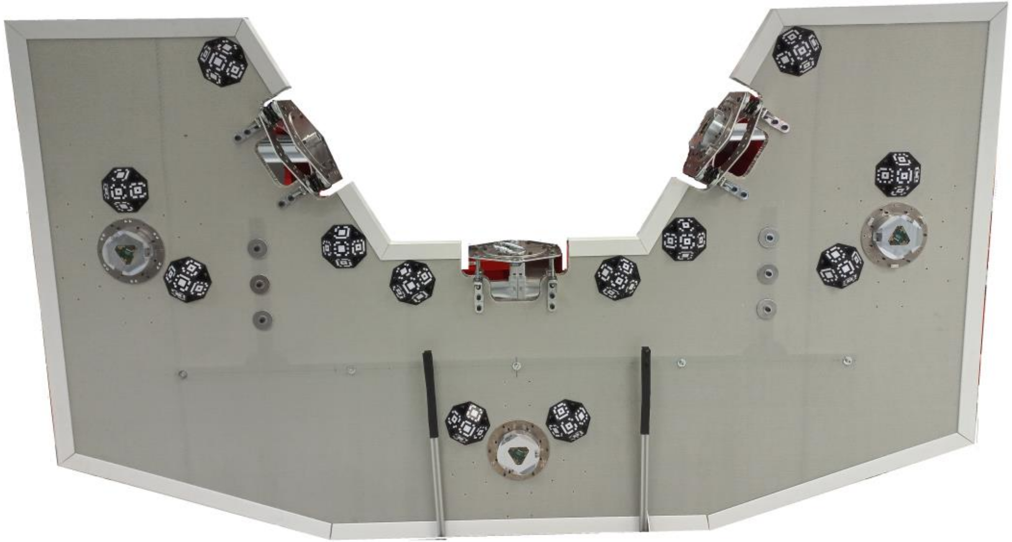


Testbed Design

Telescope/spacecraft Mock-ups

Single Mirror Tile and Telescope mock-ups
(12Kg and 25 Kg) including:

- Lightweight honeycomb panels structure
- Assembly SIROMS
- Manipulation/Locomotion SIROMS
- Fiducial markers

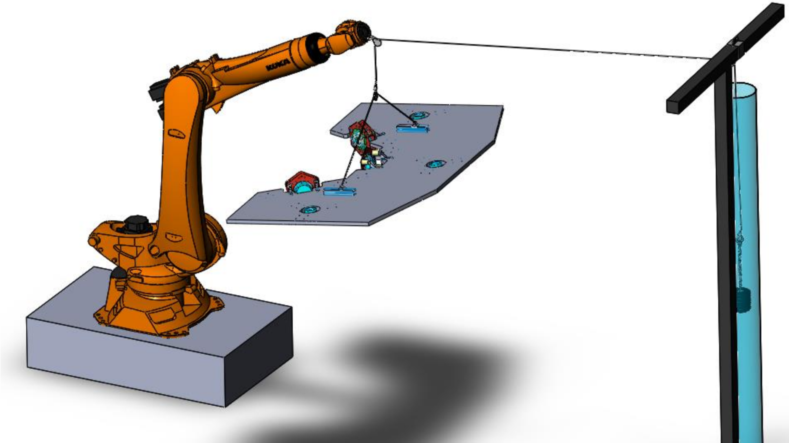


Testbed Design

Weight Compensation Device

Weight Compensation Device:

- Offloads the Telescope mock-up (25 Kg)
- WCD manipulator tracks motion of CoG of telescope mock-up
- Steel cable, pulleys and counterweight compensate weight
- Cable setup allows rotations around the telescope CoG



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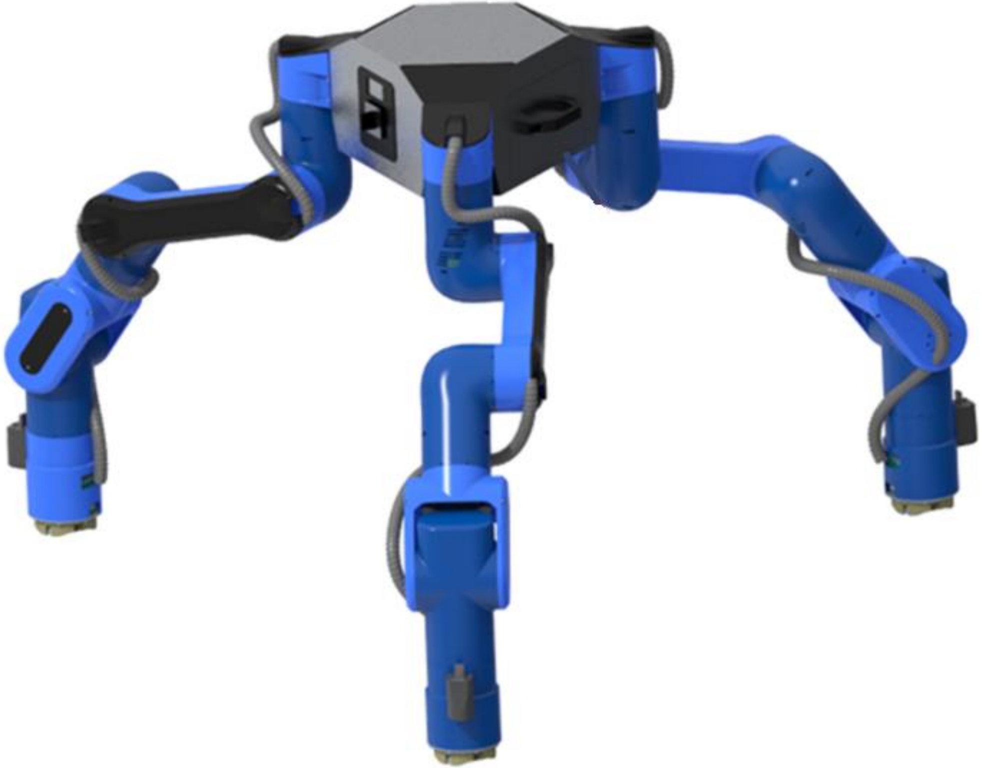


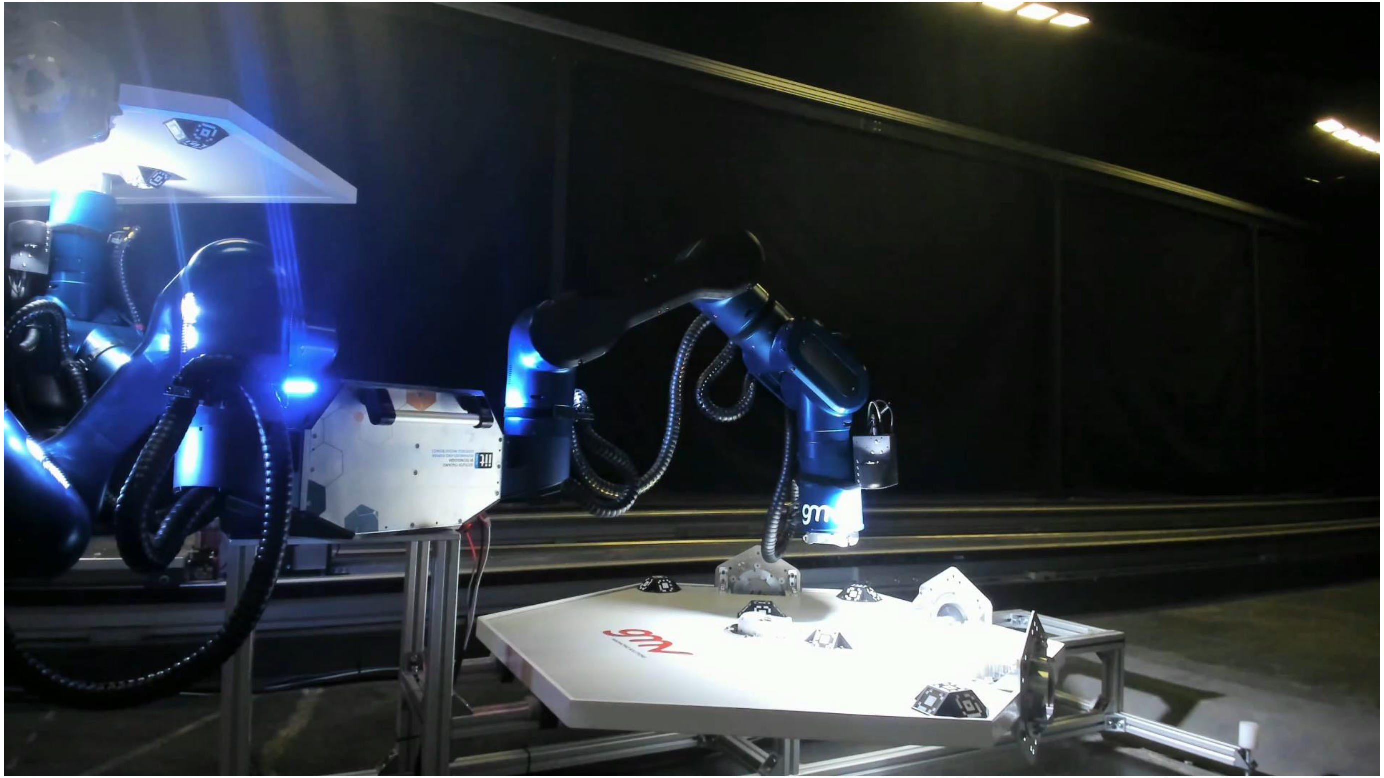
System Testing

Manipulation Test

Grasp operation phases:

1. Free motion approach
2. Visual servoing approach
3. IC Compliant latching

mirror
Multi-arm Installation Robot for Readying ORUS and Reflectors



System Testing

Locomotion Test (I)

Locomotion operation phases:

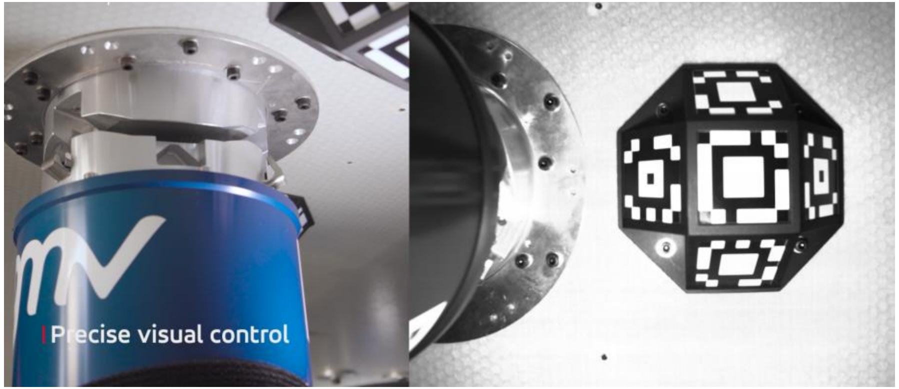
1. Free motion approach
2. Visual servoing approach
3. IC Compliant latching
4. Unlatching (another arm)
5. Body motion

System Testing

Locomotion Test (II)

- **Test:** Robot waks on the three manipulation SIROMS of the telescope
  - Weight Compensation Device used

- **Results**: all tests successful:
  - Very reliable operation (over 40 steps performed)
  - Accurate and robust eye-in-hand visual servoing (5 mm accuracy needed)
  - Smooth operation of the WCD



System Testing

Assembly Test (I)

Assembly operation phases:

1. Free motion approach
2. Visual servoing camera approach → eye-in-hand VS
3. Visual servoing assembly approach → external VS
4. IC for compliant latching

System Testing

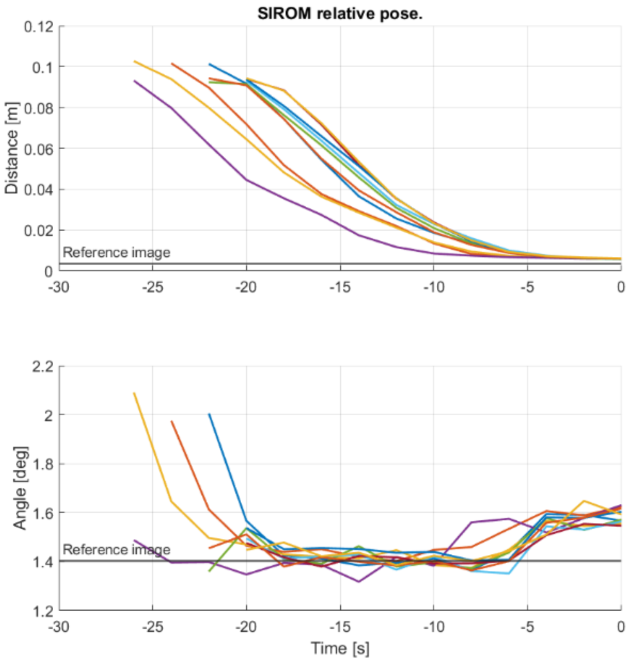
Assembly Test (II)

- **Tests**: Single / Double / Triple Assembly and Dissassembly
- **Results**: All tests successful:
  - The position/orientation accuracy needed (3mm / 1 deg) was reached consistently
  - Collisions can be expected, but they are not problematic
    → Use of IC + VS is recommended
  - Visual servoing is stable, robust and accurate, even in presence of structure vibrations
  - Consistent, repeatable results, obtained in 5 test repetitions

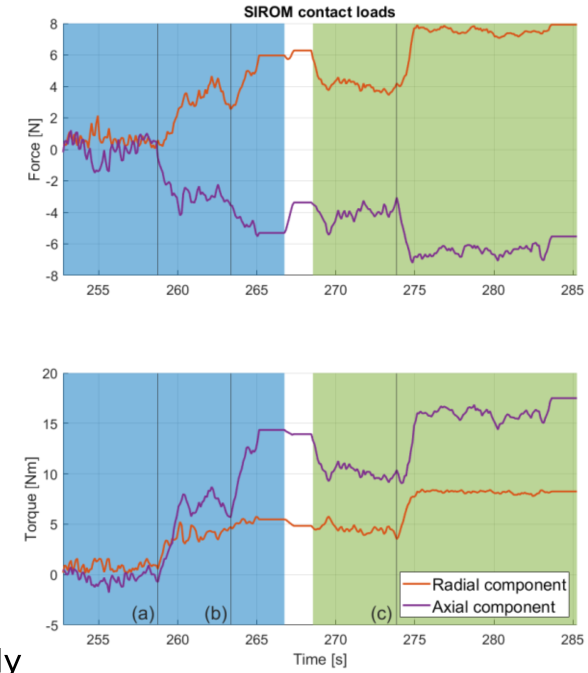
System Testing

Assembly Test (III)

Assembly operation phases:
1. Free motion approach
2. Visual servoing camera approach → eye-in-hand VS
3. Visual servoing assembly approach → external VS
4. Compliant latching



Final error: 2.7 mm, 0.17 deg



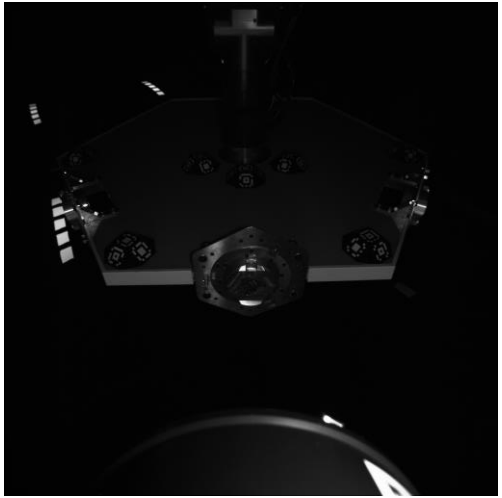
Assembly phase: 1./2. 3. 3. 4

System Testing

Light Conditions Robustness Test

- **Tests**: Triple assembly with lighting conditions:
  - Diffuse light
  - Darkness
  - Focused light near telescope plane

- **Results**: All tests successful:
  - Best results in darkness (eclipse)
  - Ligting parallel to telescope is the worst case
  - Changing light conditions can result in unstable motion
  - Exposure time adjusted manually
    - → Auto-exposure + HDR needed in a flight system
    - → A “smart” autoexposure optimising visibility of markers is proposed for a flight system

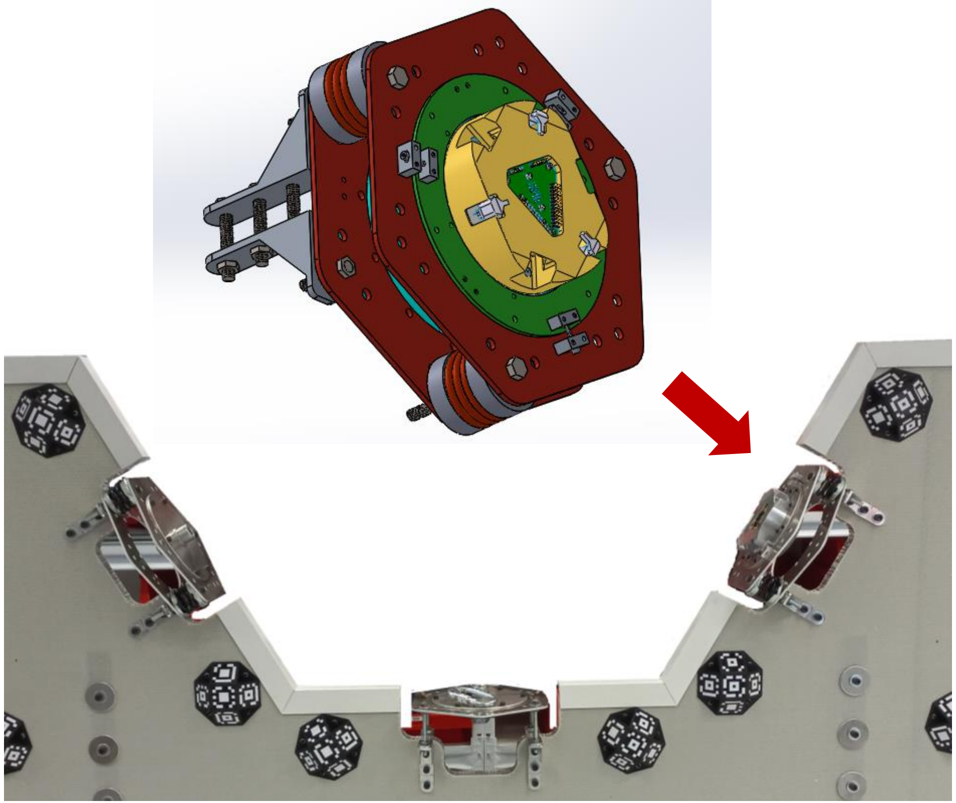


System Testing

Structure Misalignment Robustness Test

- **Tests**: Triple assembly with SIROM misalignment conditions:
  - 0 mm misalignment
  - 1 mm misalignment
  - 2 mm misalignment

- **Results**: Successful for misalignment < 2mm
  - Failure to complete the latching (mechanically) for 2 mm misalignment
  - MIRROR robot performance is good even in misalignment conditions



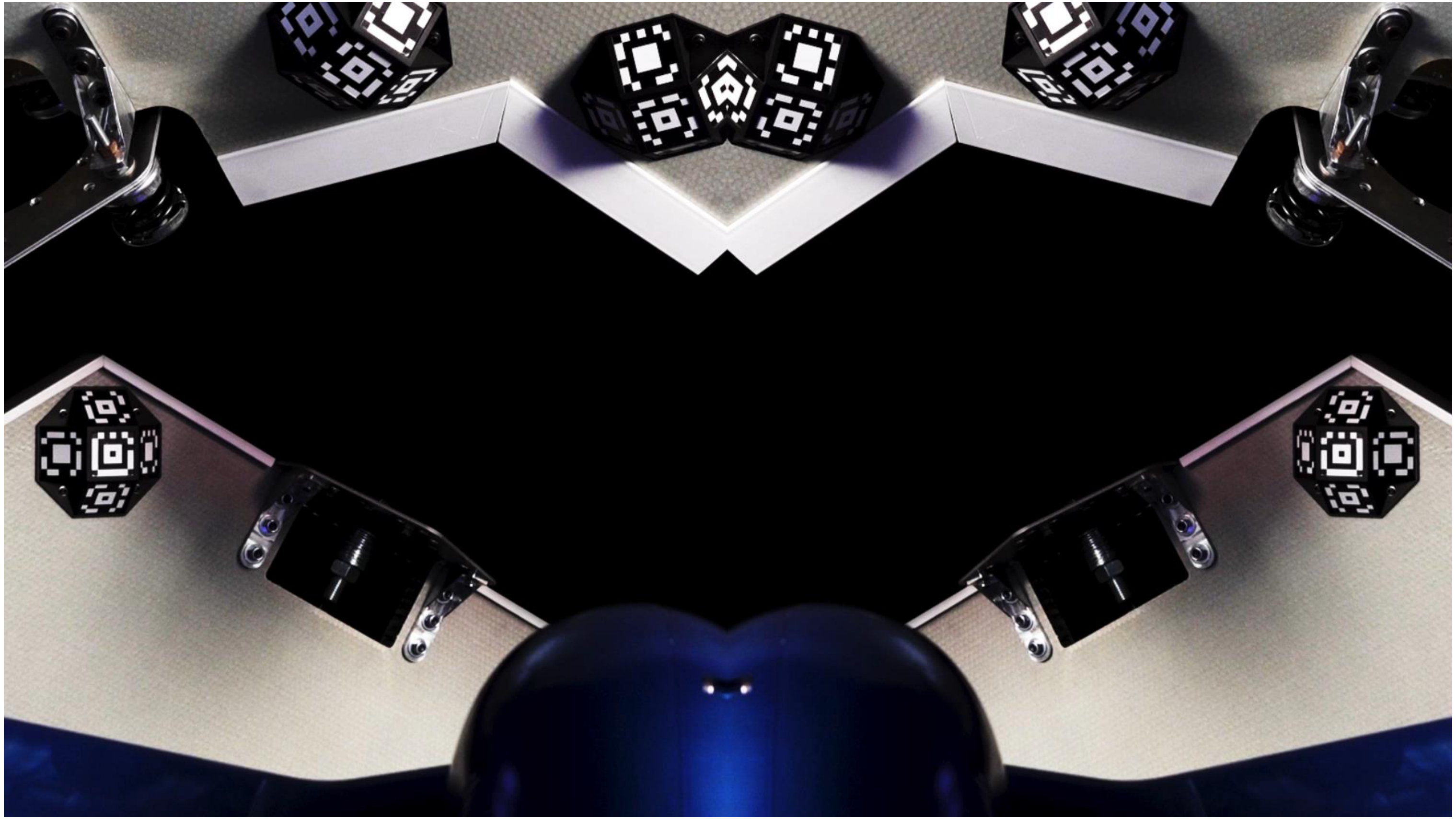
Conclusions

MIRROR activity conclusions and way forward

- The whole concept for a re-locatable manipulator for on-orbit assembly has been validated succesfully, including:
  - The sensor approach, based on three cameras and joint torque sensors
  - The vision-based and force-based control approach for precise and safe manipulation and assembly

- The breadboard system has been developed and tested in ground up to TRL4

- Next steps should address aspects not covered in the activity:
  - On-orbit representative testing conditions for vision, Autoexposure+HDR, etc.



Thank you

MIRROR Team