ESA ASTRA 2023

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

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mirror
Multi-arm Installation Robot for Readying ORUS and Reflectors

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# Introduction

- **Multi-arm Installation Robot for Readying ORUS and Reflectors (MIRROR)**

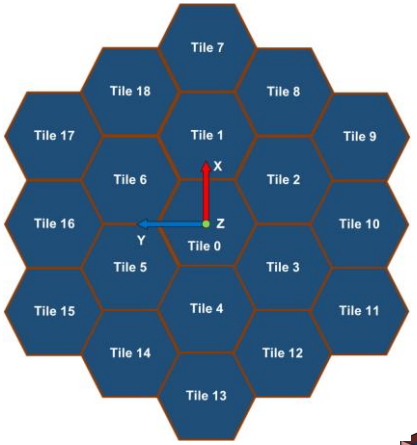
- ESA contract covering preliminary design (flight system) and development and ground testing of a breadboard demonstrator (TRL4)

- Industrial Consortium:

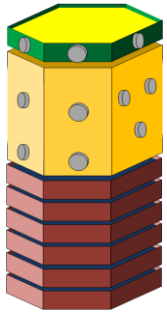
# Mission and Concept of Operation (I)

## Scenario

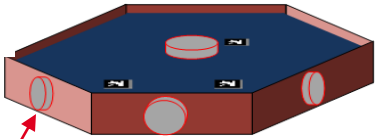
On-orbit Assembly of a Multi-Ring Telescope Reflector




Tiled Reflector



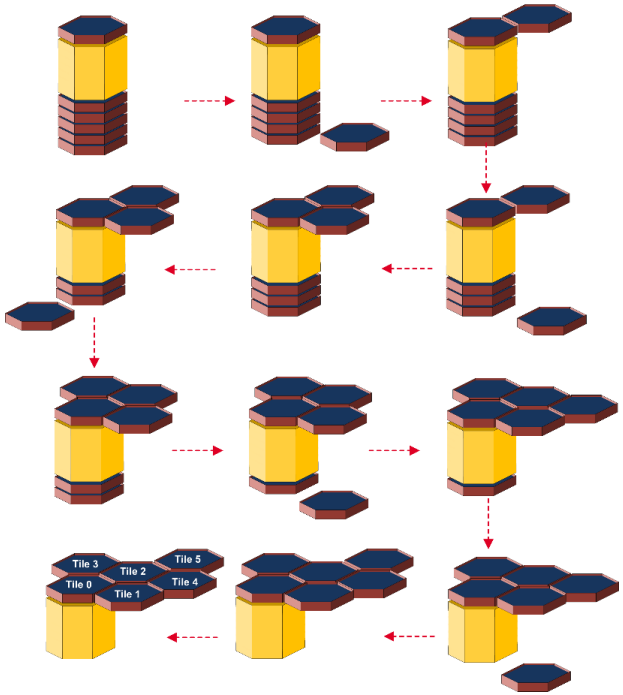
Telescope Spacecraft



Single Mirror Tile

Standard Interconnects

Launch Configuration

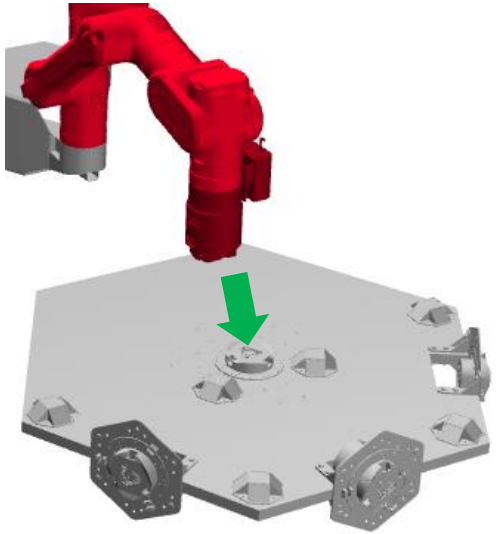



On Orbit Assembly

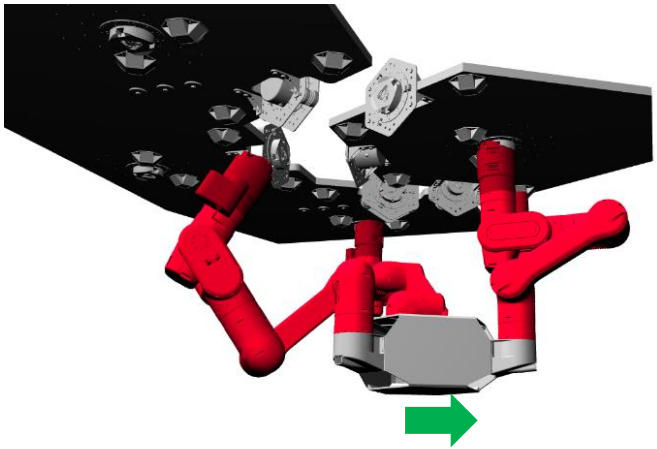
# Mission and Concept of Operation (II)

## Concept of Operation

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

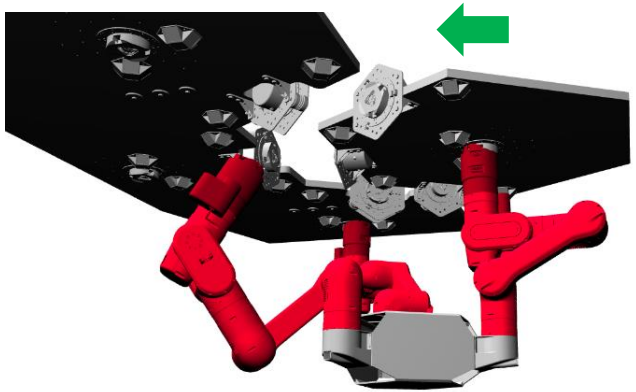


**Tile Manipulation**



**Locomotion & Tile Transport**

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



**Tile assembly**

# MIRROR Features

## Vision System

**3 Camerras and ligts near end-effectors**

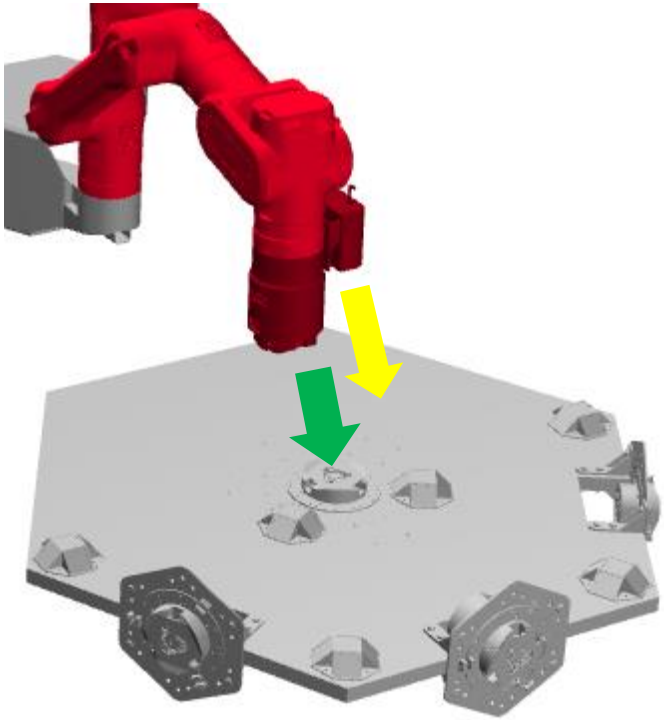
**3D fiducial markers**

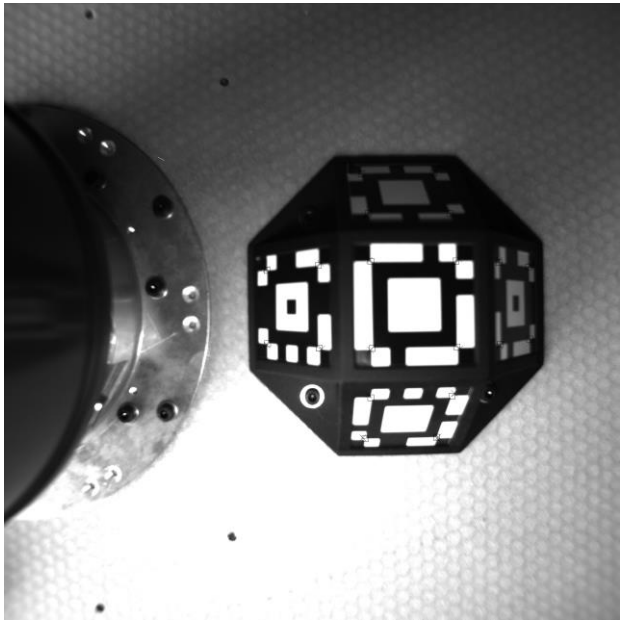
**Image Based Visual Servoing:**

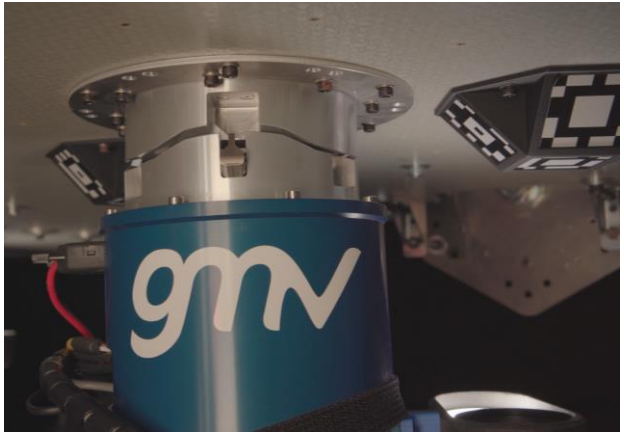
- Eye-in-hand Visual Servoing: Manipulator Attach
- Eye-in-head (external): SMT Assembly

# MIRROR Features

## Visual Control: Eye-in-hand Visual Servoing

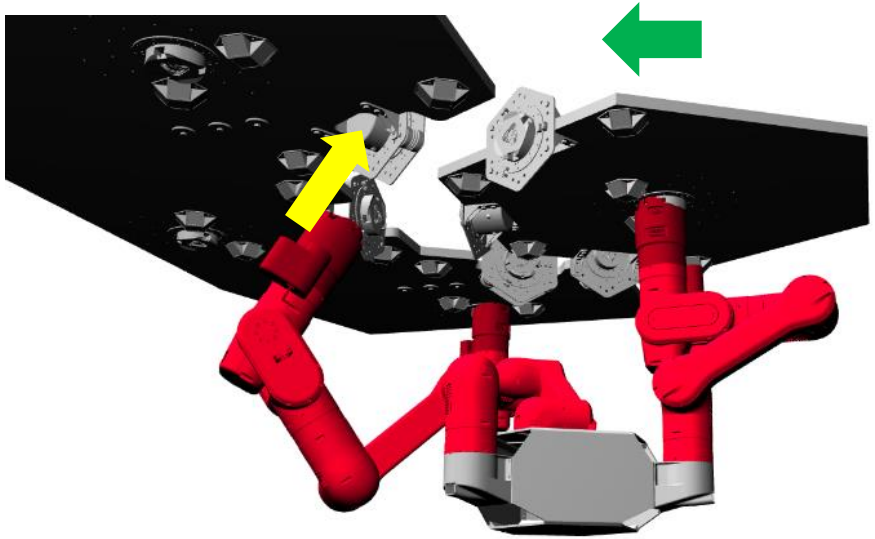


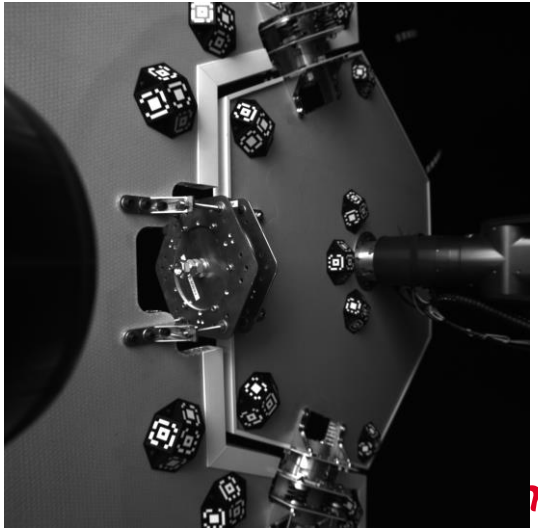




# MIRROR Features

## Visual Control: External visual servoing



# MIRROR Features

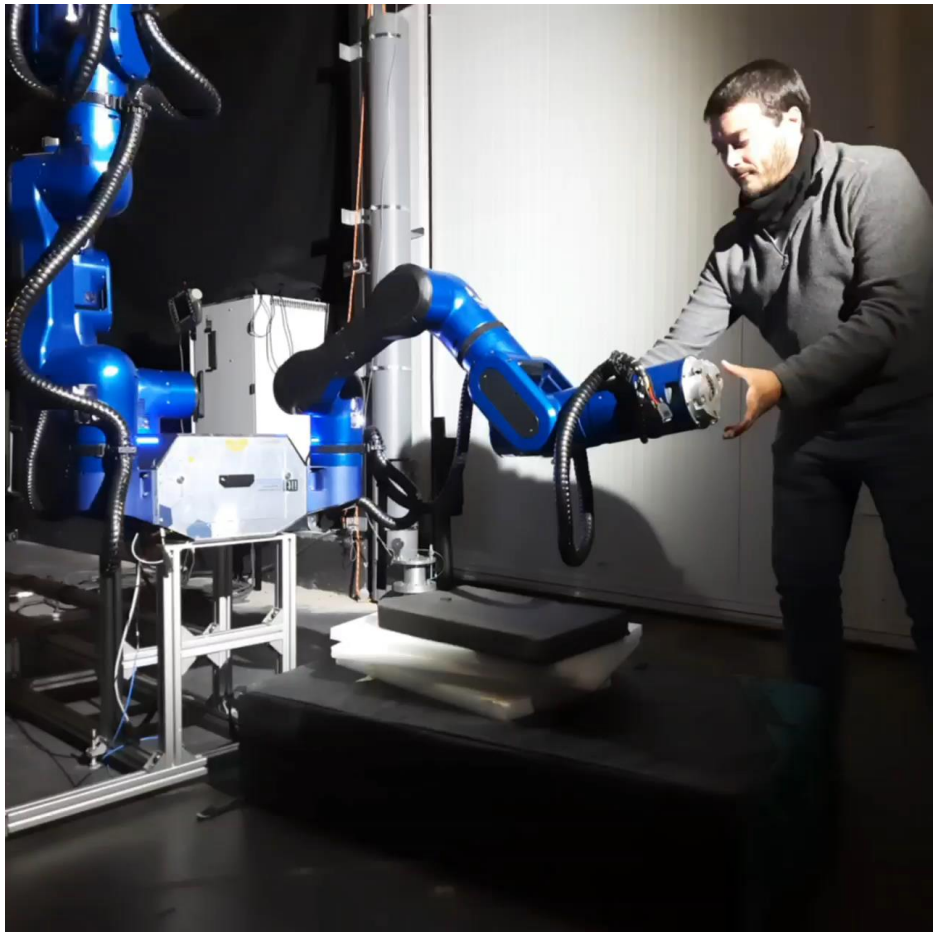
## Force-based Control

**Impedance Control (IC)**

**Gravity compensation used for ground testing**

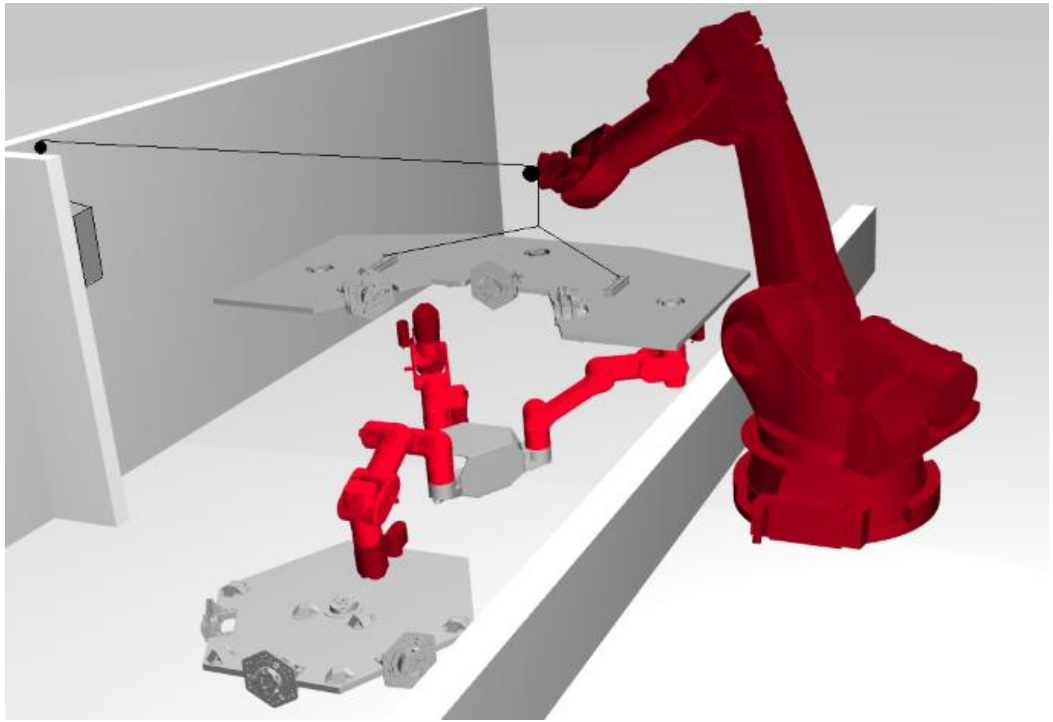
**Two IC use cases:**

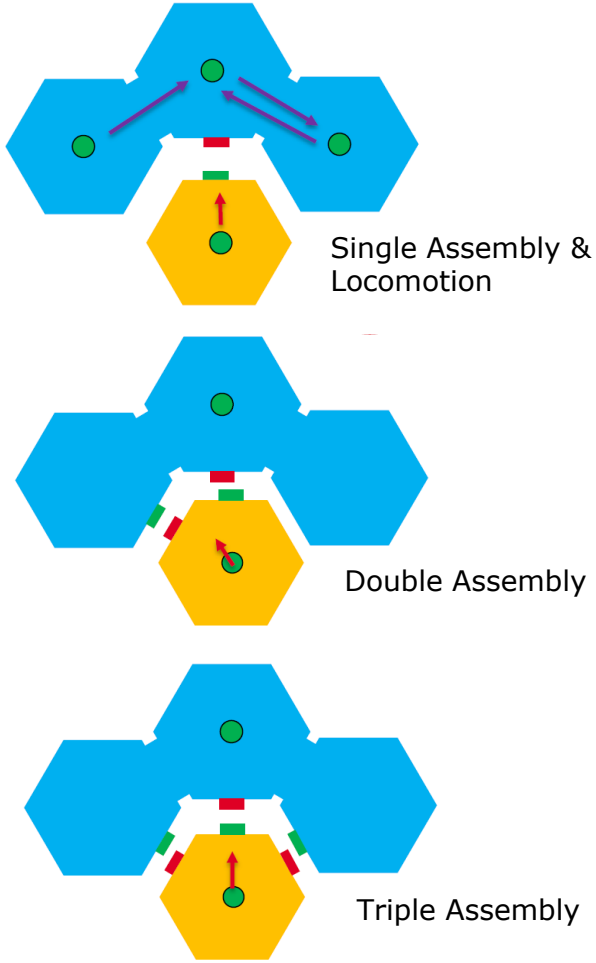
- Safe Visual approach for SMT Assembly and Manipulator Attach
- Force relaxation for SIROM latching



# System Testing

## Ground Test Setup



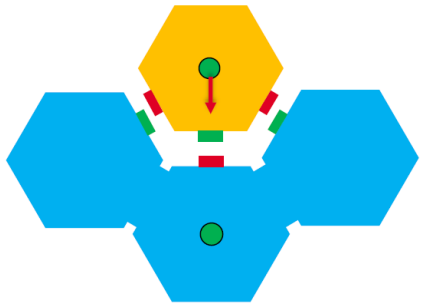


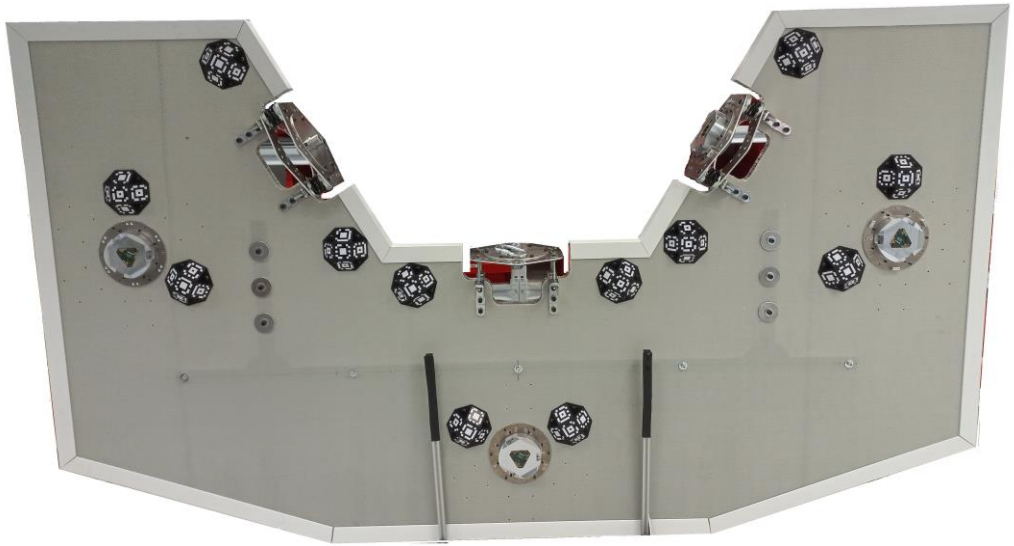
# Testbed

## 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



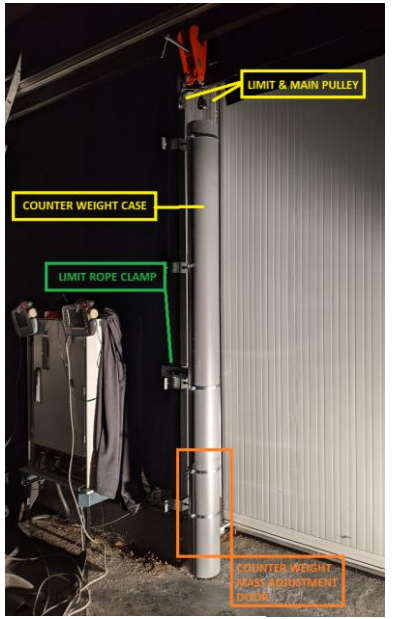


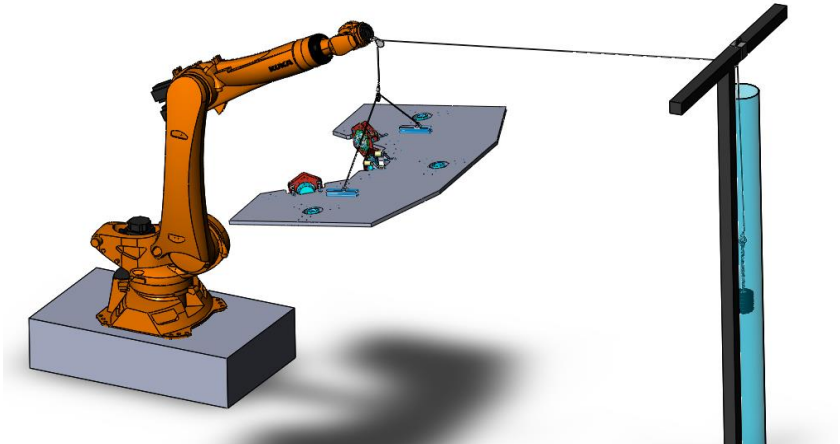
# Testbed

## 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



# System Testing

## Manipulation Test

**Grasp operation phases:**

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

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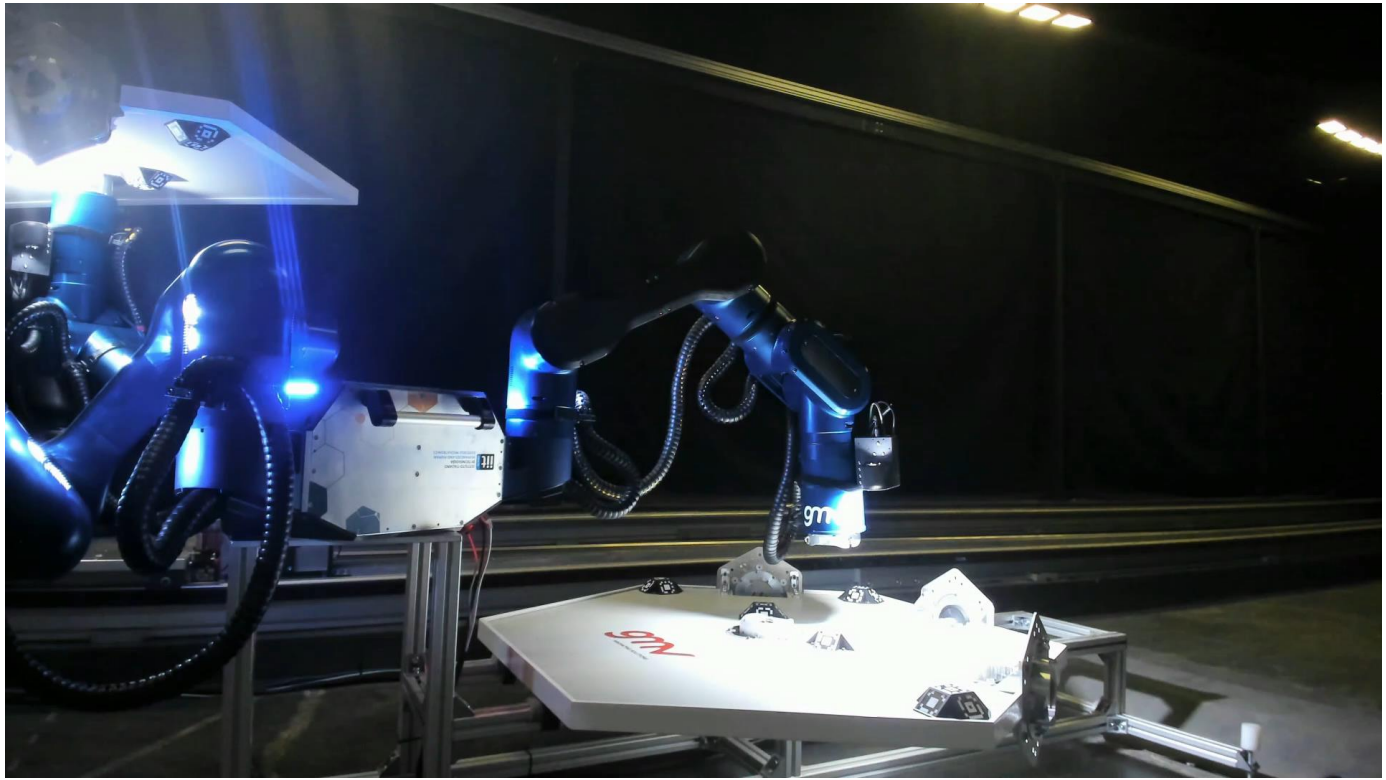

# System Testing

## Locomotion Test (I)

**Locomotion operation phases:**

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

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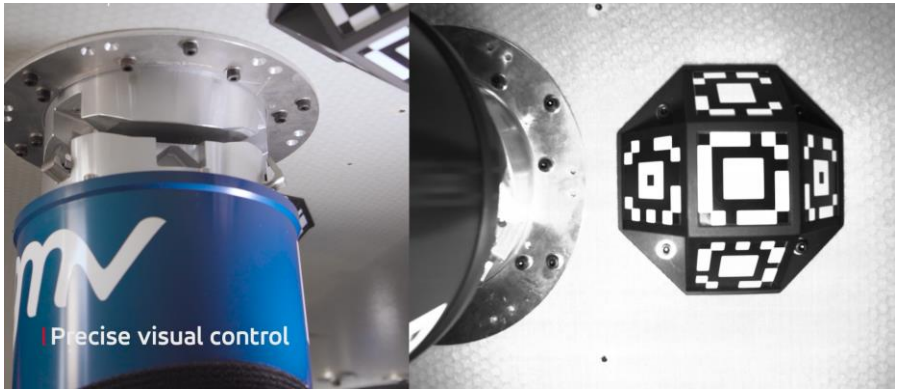
# System Testing

## 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)

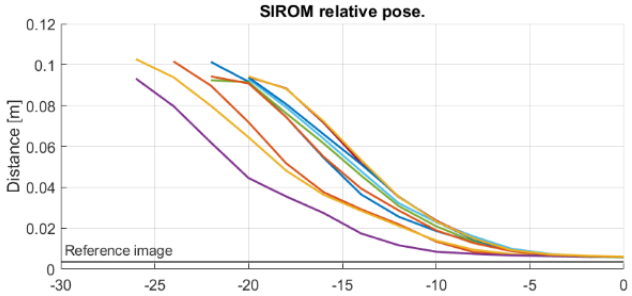
- **Tests**: Single / Double / Triple Assembly and Dissassembly
- **Results**: All tests successful:
  - The position/orientation accuracy needed (3mm / 1 deg) was reached consistently
  - Collisions can be expected, but they are not problematic
    → Use of IC + VS is recommended
  - Visual servoing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

# System Testing

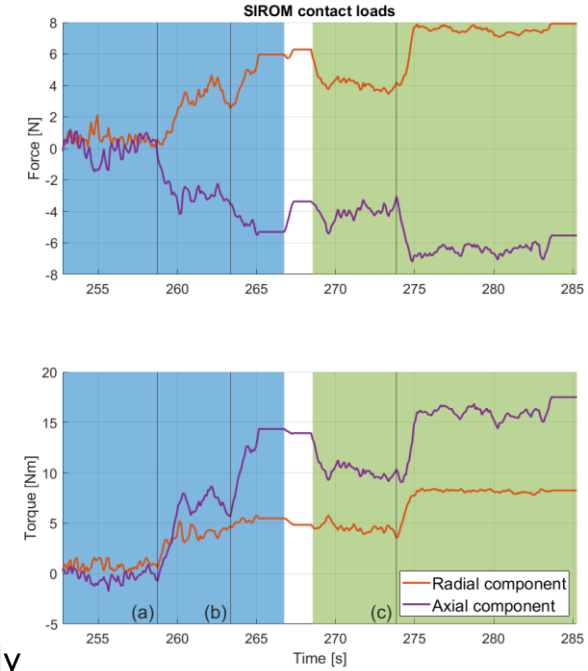
## Assembly Test (III)

**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

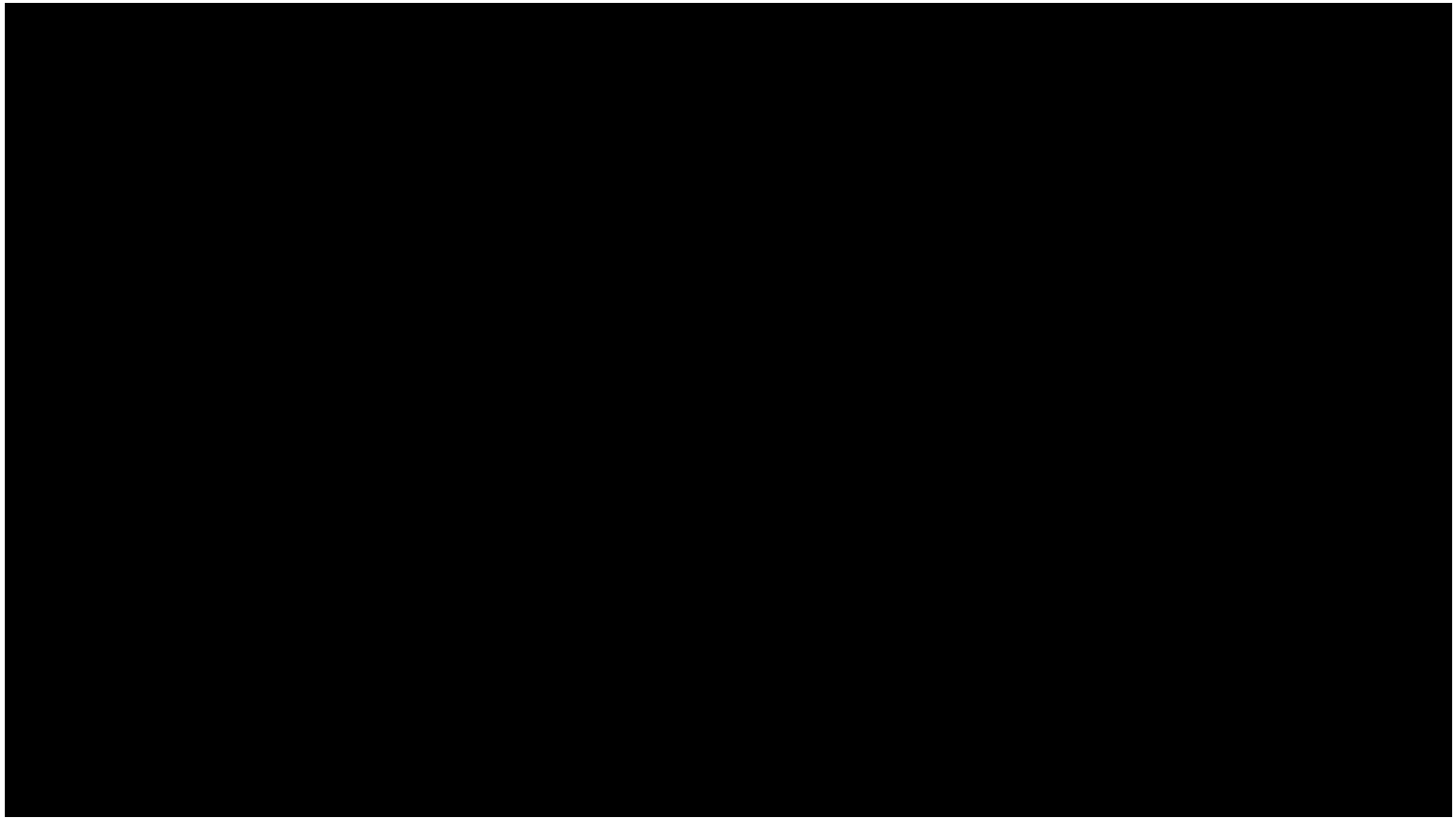
# Conclusions

## 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.



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# Thank you

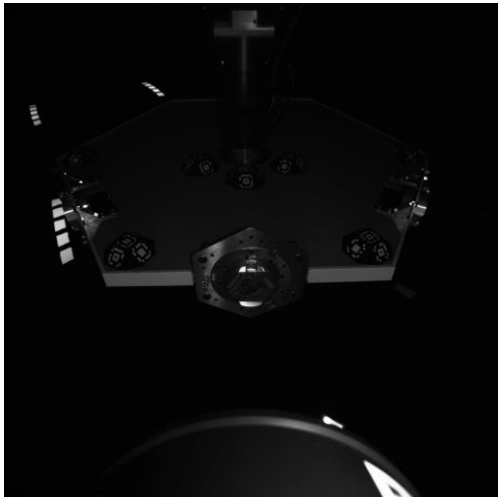
MIRROR Team

# 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

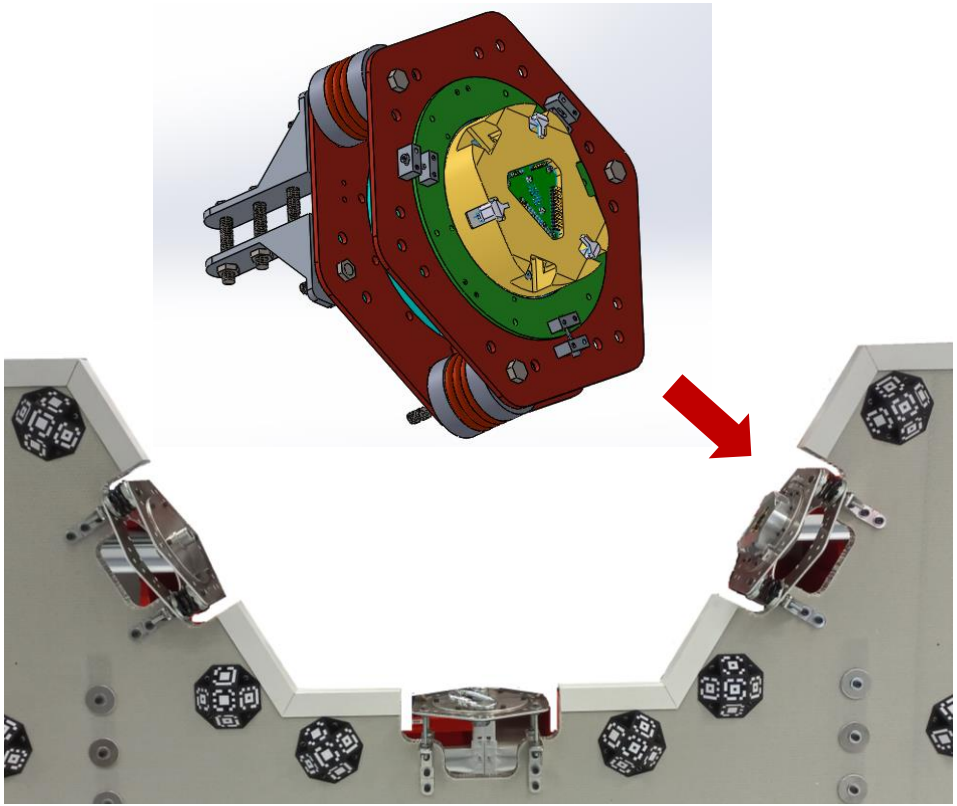


# System Testing

## Structure Misalignment Robustness Test

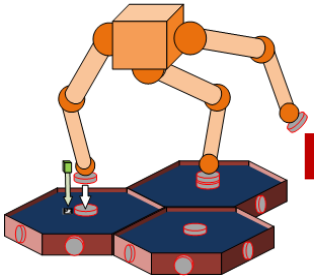
- **Tests**: Triple assembly with SIROM misalignment conditions:
  - 0 mm misalignment
  - 1 mm misalignment
  - 2 mm misalignment

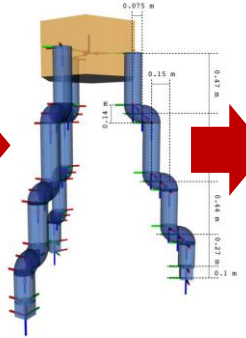
- **Results**: Successful for misalignment < 2mm
  - Failure to complete the latching (mechanically) for 2 mm misalignment
  - MIRROR robot performance is good even in misalignment conditions

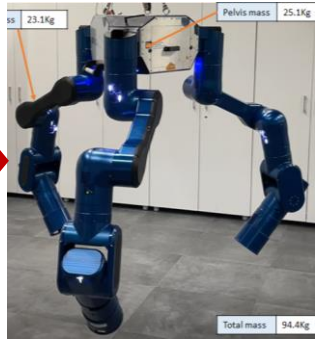


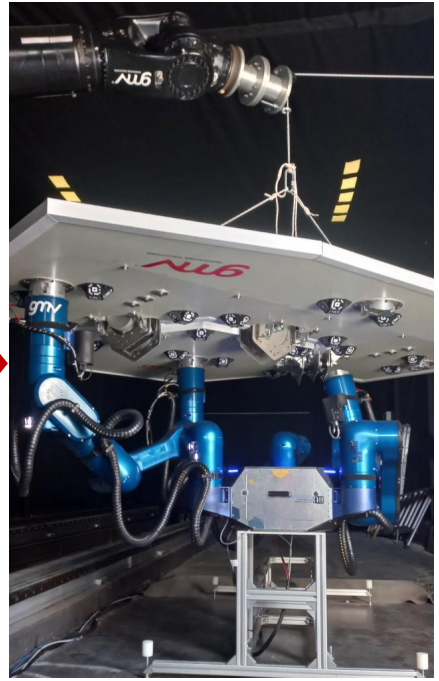
# Flight/Breadboard System Development

## 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**