Clean Space Industrial Days 2018

COMRADE - FULLY COMBINED CONTROL FOR ROBOTIC SERVICING SPACECRAFT

INNOVATING SOLUTIONS

COMRADE: CONTROL & MANAGEMENT OF ROBOTICS ACTIVE DEBRIS REMOVAL

- **ESA** funded TRP

- Furthering technology for ADR/Servicing
  - Reducing the number of debris objects in space.
  - Extending life or repairing damaged on-orbit assets attractive economic option for satellite operators

- **Technical challenges Robotic Servicer**:
  - Control of **uncertain coupled dynamics** (spacecraft platform + robotic manipulator + and end-effector)
  - Synchronization with **fast tumbling** targets
  - Limitation of structural **loads** on arm

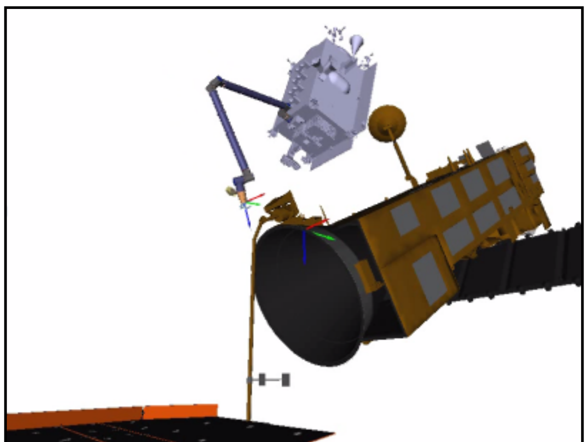
gmv

FULLY COMBINED CONTROL

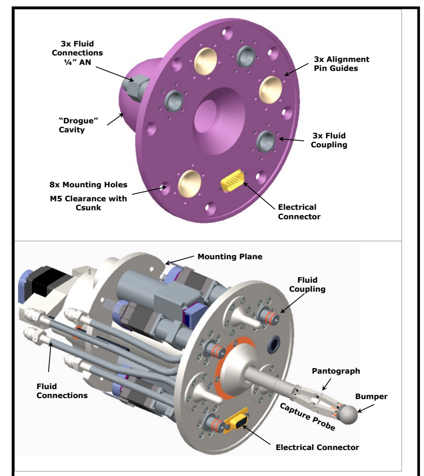
- **Fully combined control** (alternative to decoupled, tele-op, *collaborative*)
  - overcome the problem of arbitrary, case-tailored control authority, improve performance, savings

- Two control design approaches:
  - **H∞** and
  - nonlinear **compliant Lyapunov-based**).

ADR eDeorbit



Servicing (ASSIST)

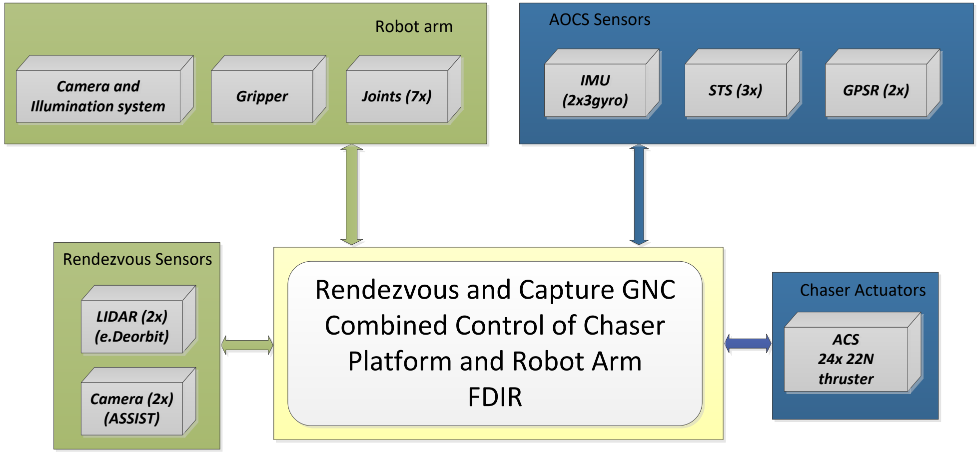


SYSTEM SPECIFICATION

Robotic Servicer Elements:

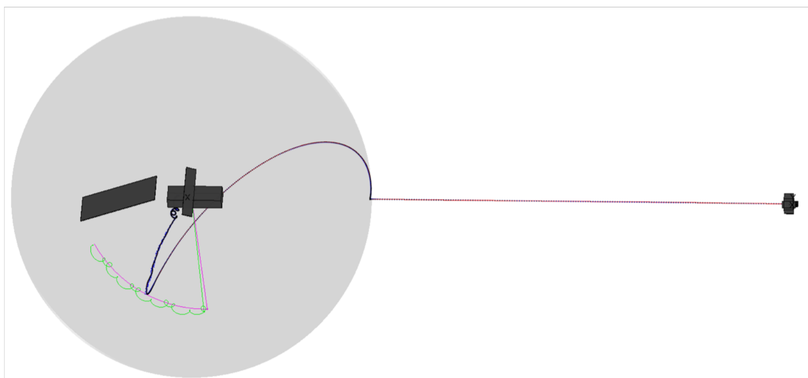
- AOCS sensors: **IMU, star tracker, GPS**
- Propulsion: **24x22 N** thrusters (eDeorbit-based)
- Relative navigation:
  - **LIDAR** for eDeorbit scenario
  - **Vison-based** camera for re-fueling scenario
- Robotic manipulator: **7 DOF** with joint encoders
- End-effector:
  - PIAP developed **gripper** for eDeorbit scenario
  - **ASSIST re-fueling** device developed by a team led by GMV
- Control analysis and synthesis considers:
  - Fuel **sloshing**
  - **Flexible modes** (solar arrays and robotic manipulator)
  - **Arm dynamics**

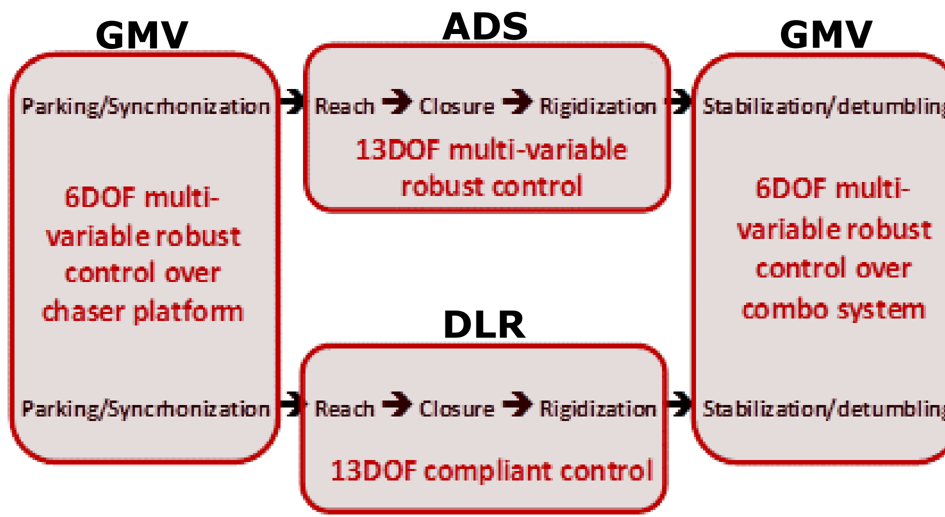
Architecture



MISSION PHASES

- Angular/linear **Synchronisation** of Chaser wrt target rotation
- **Reach and Capture** (Robotic arm deployment and target grasping)
- **Rigidisation** of robotic arm joints
- **Stabilisation/detumbling** of target rotation (for ADR case only)





GNC SYSTEM REQUIREMENTS

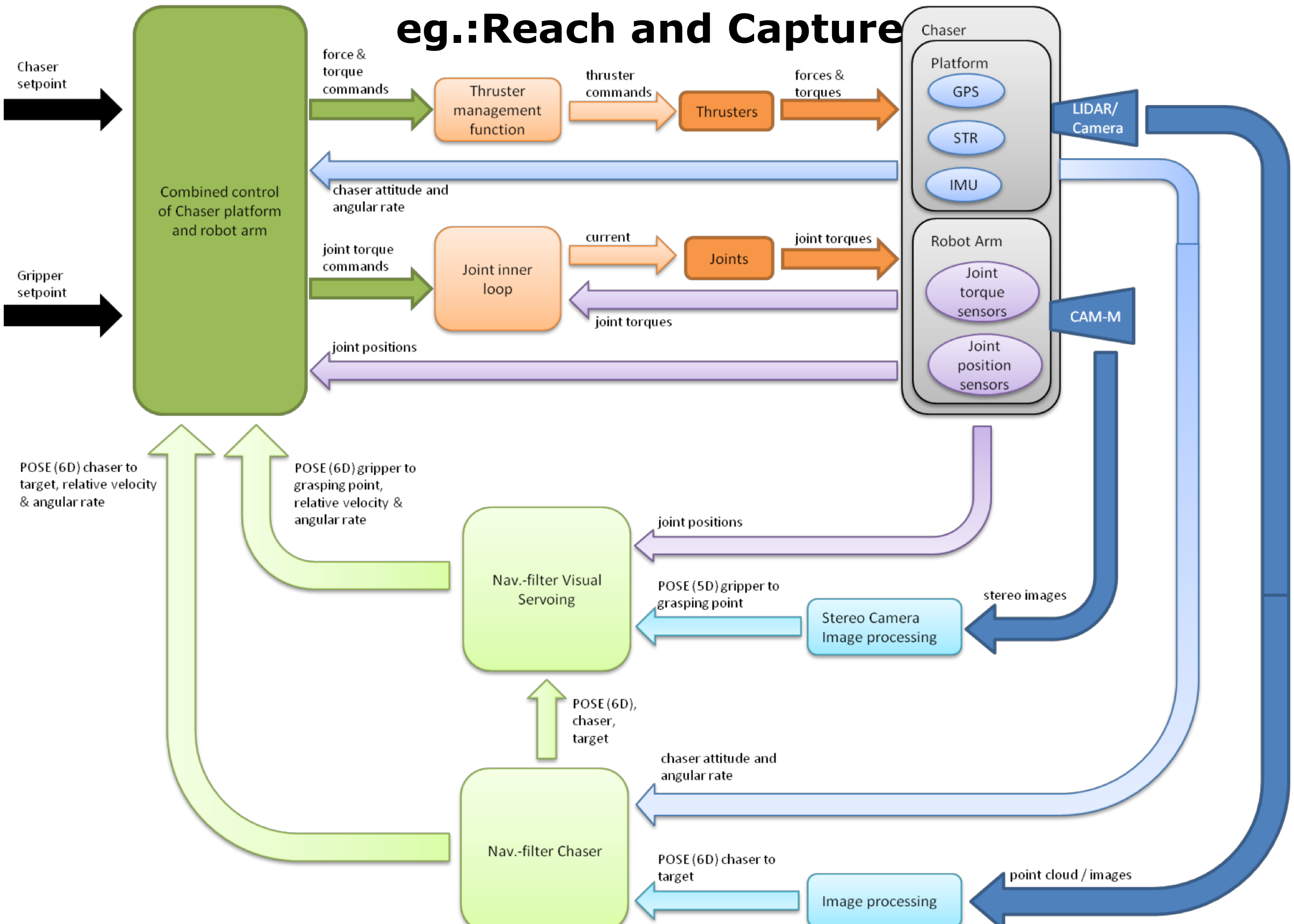
Performance requirements:

- **Synchronization** control performance requirements (95%) for relative state (CoM to CoM):
  - **[100 mm 10 mm/s 2° 0.5°/s]** (6DOF control)
- **Reach & Capture** control performance requirements (95%) for relative to TGFF:
  - **[50 mm 5mm/s 2° 0.5°/s]** (CoM wrt to point in TGFF)
  - **[10mm 5mm/s 2° 0.1°/s]** (end-effector wrt to grasping point)
- **Stabilisation** control performance requirements (2σ):
  - Angular rate of chaser+target dampened to **0.5°/s.**

Safety requirements:

- **Synchronization/Reach/Capture**:
  - Distance between chaser platform and target surfaces larger than **0.5m**.

ARCHITECTURE

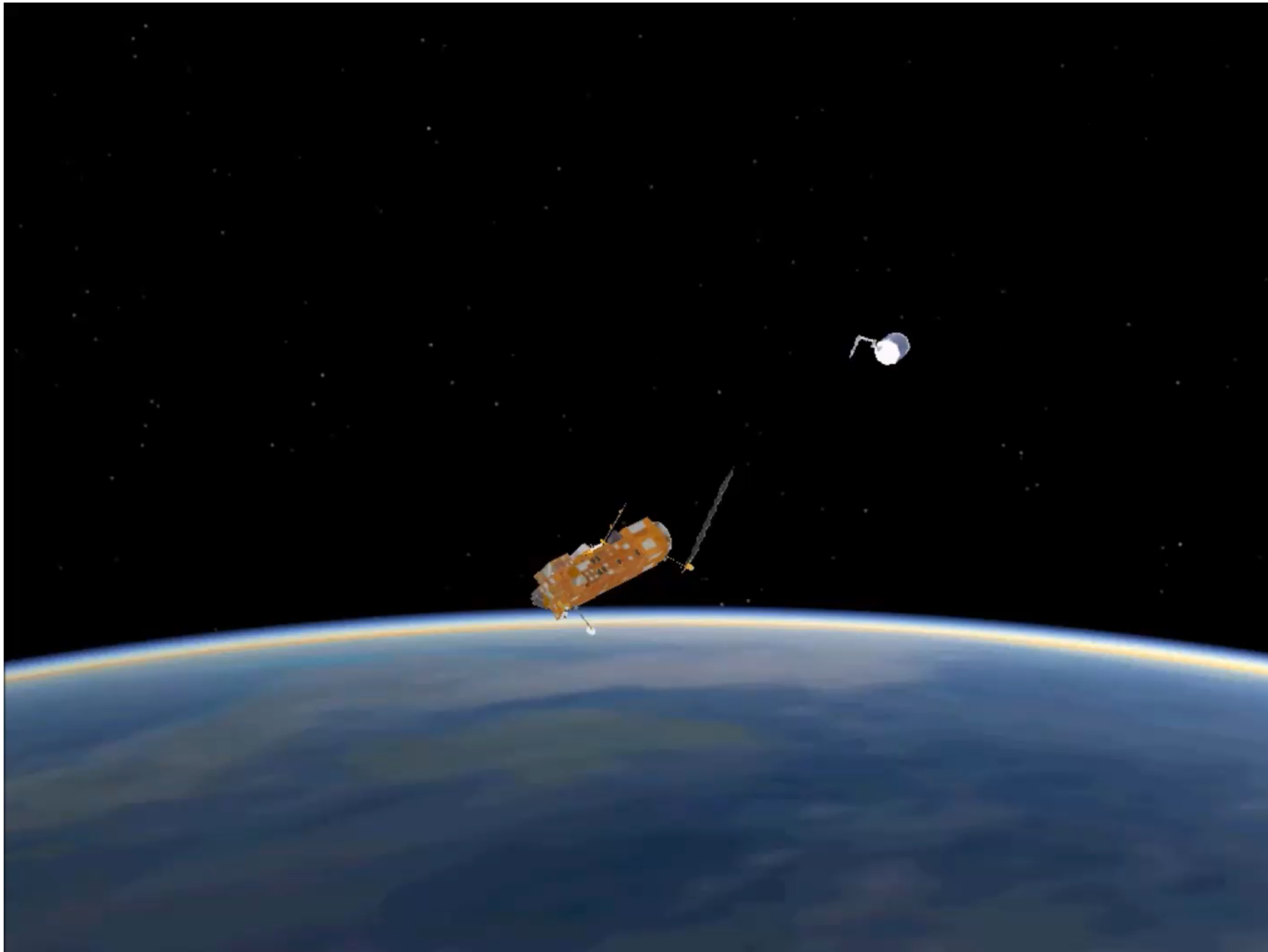


MISSION PHASES

- **Synchronisation**
  - Robot arms is not active
  - Forced motion to profile computed by guidance
- **Reach and Capture**
  - Station keeping at capture point
  - Gripper moves towards LAR
  - Control issues: Force and Torque to RCS , Joint Torque Commands
  - Capture = Reach + Gripper control (closure command)

  *compliant control : stiffness and damping for end effector, chaser at set point
- **Rigidisation** of robotic arm joints:
  - Thruster commands are inhibited
  - Angular rates of joints controlled to zero
  - Locking brakes are engaged
- **Stabilisation/detumbling** of target rotation (for ADR case only) – limit for joint torquers
- **Escape** : combined control that tracks a collision-avoidant guidance

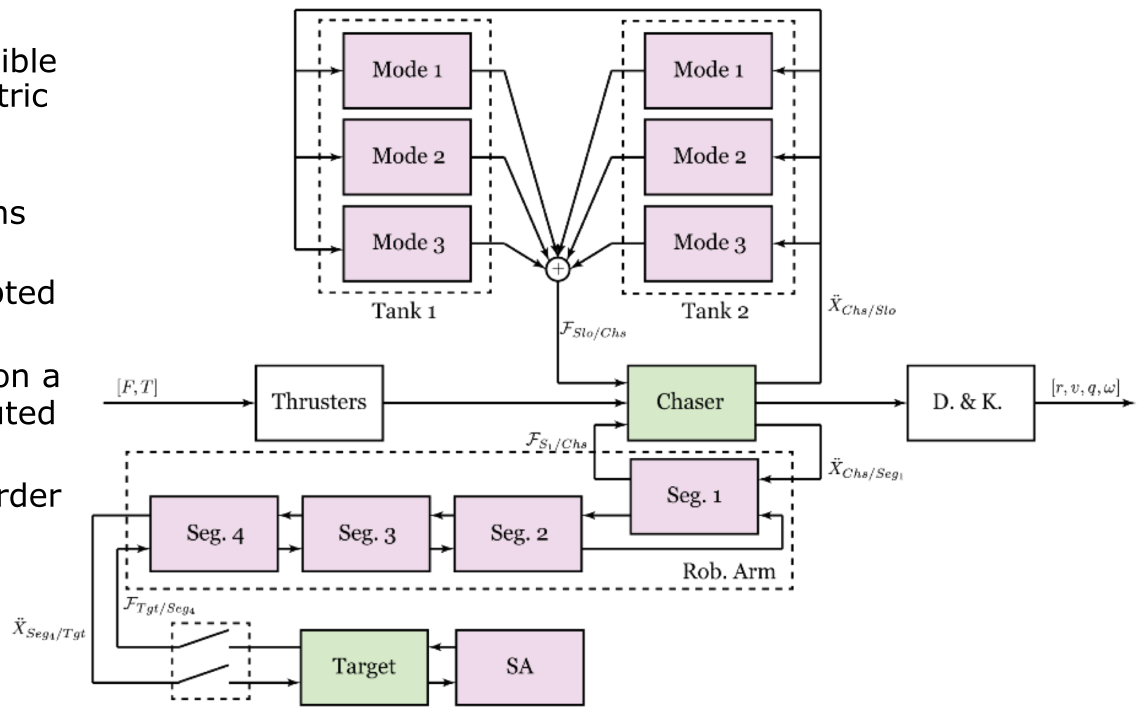
SYNCHRONISATION



CONTROL SYNTHESIS & ANALYSIS

H_∞ synthesis / μ-analysis:

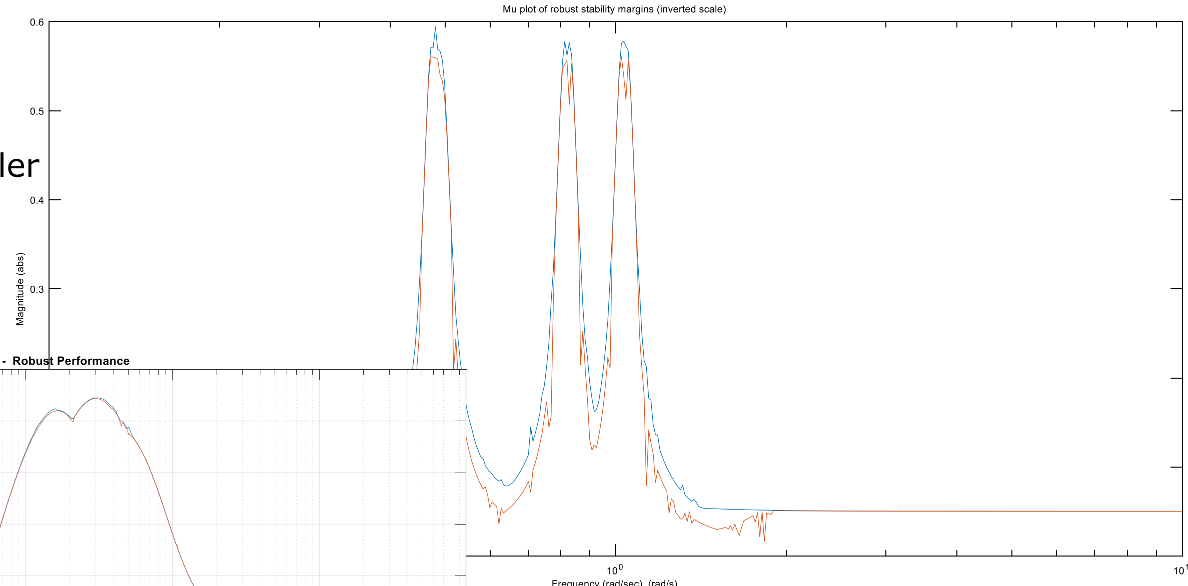
- **LFT** representation of the linearized flexible spacecraft model to account for parametric **uncertainty**.
- **Two-Input Two-Output** Port (TITOP) modelling paradigm for multi-body chains *[D. Alazard, J. Alvaro Perez et al.]*
- The control synthesis methodology adopted is H_∞ **Mixed Sensitivity** Design.
  - The H_∞ control approach is added upon a nonlinear precompensation by computed torque control (feed-forward)
  - Shaping the sensitivity functions in order to achieve robust stability and performance.
  - Requirements are translated into frequency domain weights (of MIMO nature).

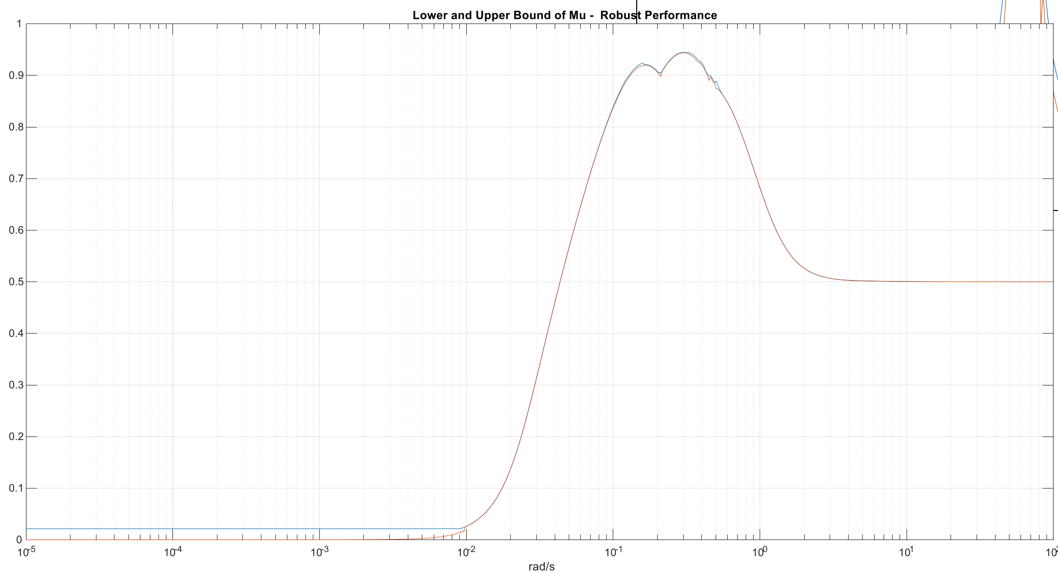


CONTROL SYNTHESIS AND ANALYSIS

Synchronization phase

μ-analysis results for
Synchronization H_∞ controller
Robust stability

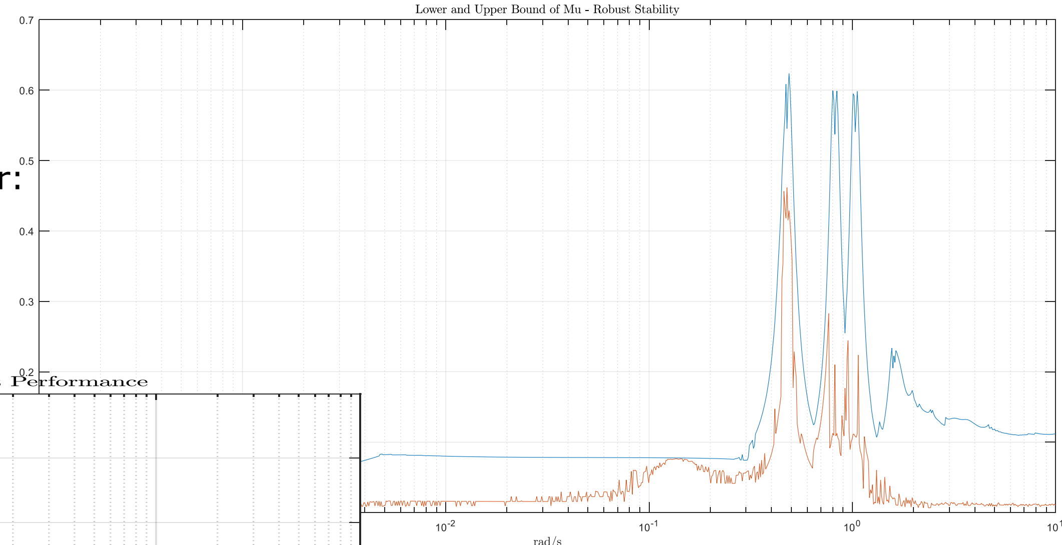


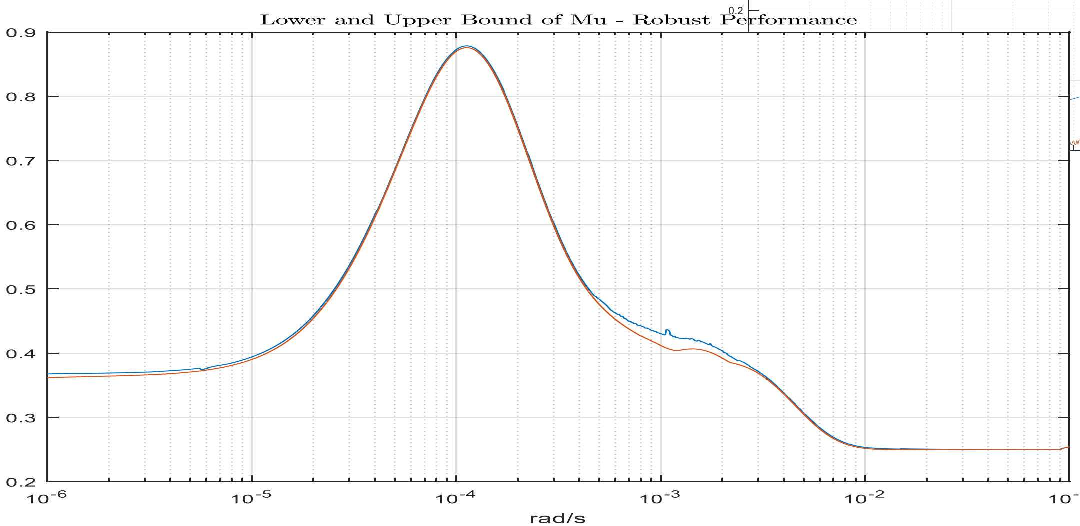


μ-analysis results for
Synchronization H_∞ controller
Robust performance

CONTROL SYNTHESIS AND ANALYSIS

μ-analysis results for
Stabilization H$_\infty$ controller:
Robust stability





μ-analysis results for
Stabilization H$_\infty$ controller:
Robust performance

CONTROL SYNTHESIS AND ANALYSIS

Non-linear compliance control method:

- Impedance controlled arm is able to follow a **given trajectory** in free motion, and at the same time exhibits a **desired disturbance response** (i.e. impedance) when in contact with the environment.
- Shaping only the **stiffness and damping**, while keeping the inertial behaviour unchanged.

- **Reach/Capture** phase:
  - Generalization of **passivity based** compliance.
  - Aiming at a closed loop structure as the one resulting from **PD+ control** in case of fixed base manipulators.
  - **Stability analysis** (an **strict Lyapunov function** for the PD+ control is available in literature, proving asymptotic stability).

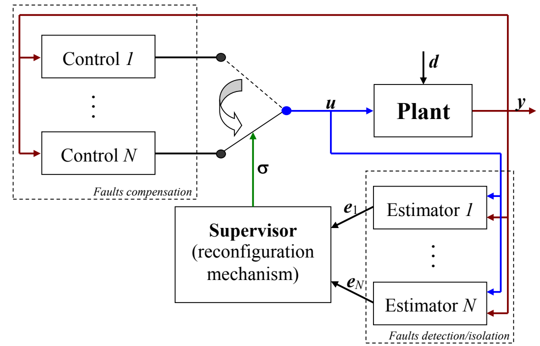
- **Rigidization phase**
  - Damping of the remaining relative velocity.
  - A PD control with bounded input (saturation effect) has been used.
  - Stability is proved in literature under the condition that the **saturation function** for the PD torque controller must be *a strictly increasing linear saturation function*.

HEALTH MONITORING SYSTEM

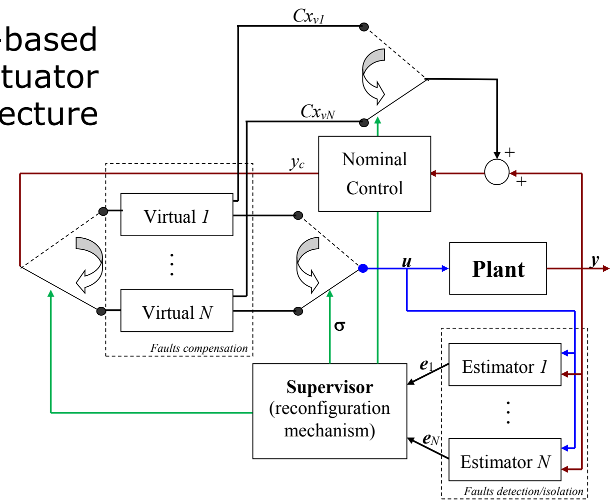
Failure Tolerant Control (FTC) system:

- Failure **Detection and Isolation** (FDI)
  - 4 of the 24 thrusters have been identified as the most problematic from a FDI viewpoint (stuck-open or stuck-closed failures)
  - Bank of 4 dedicated H∞ UIOs
- The **Accomodation** of the failure (after isolation) through the use of the system total or partial redundancies
  - The dwell-time supervisory-based FDA solution (recently extended, by IMS Laboratory to the virtual actuator paradigm).
  - Goal: select timely the suitable FTC controller from a bank of virtual actuators.

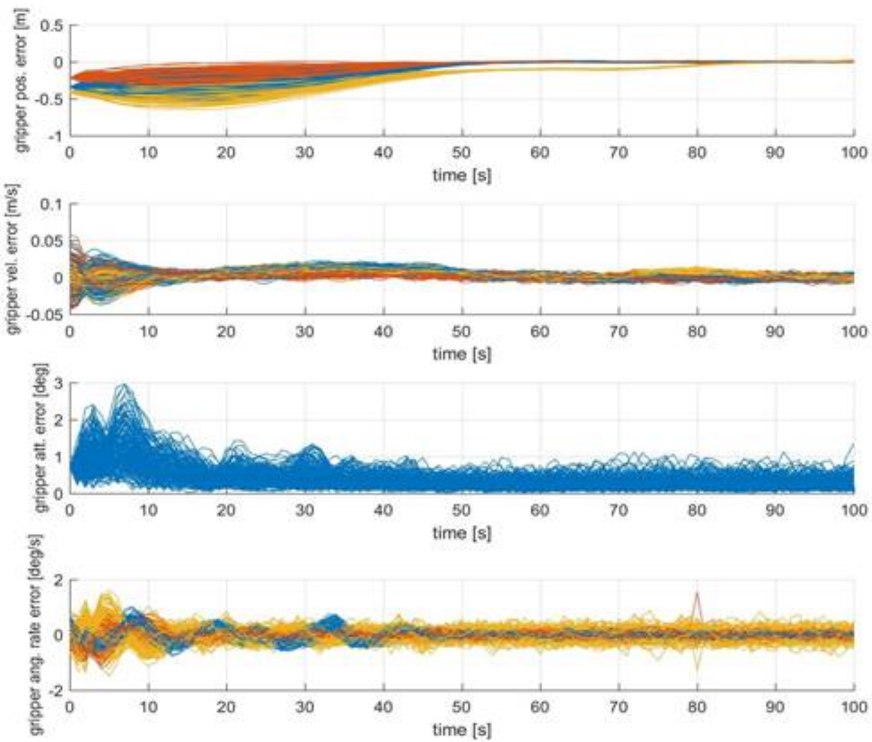
Supervisory FDA architecture



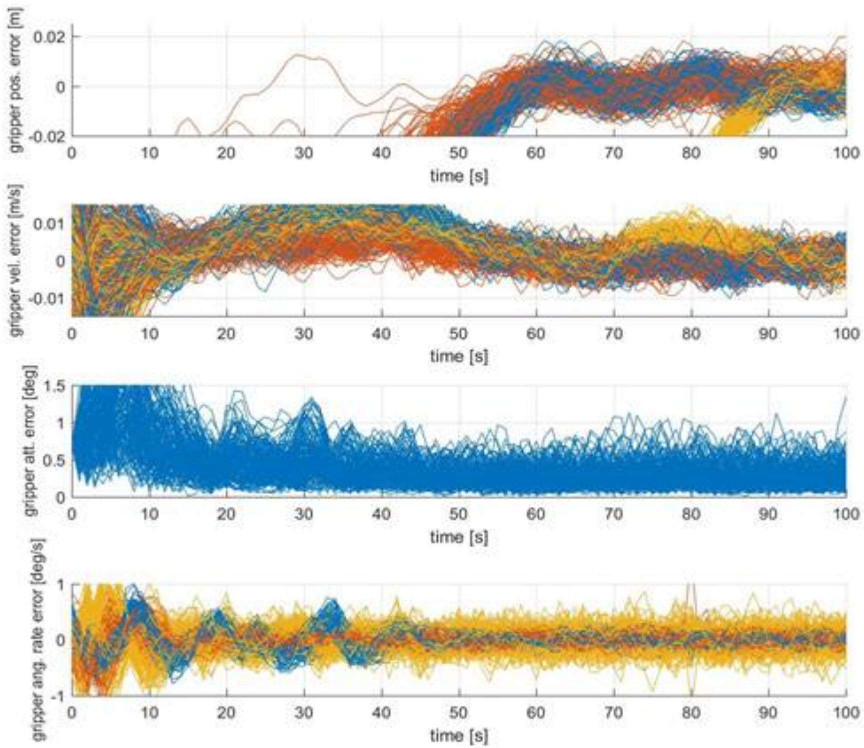
Supervisory-based virtual actuator architecture



RESULTS (MONTECARLO)

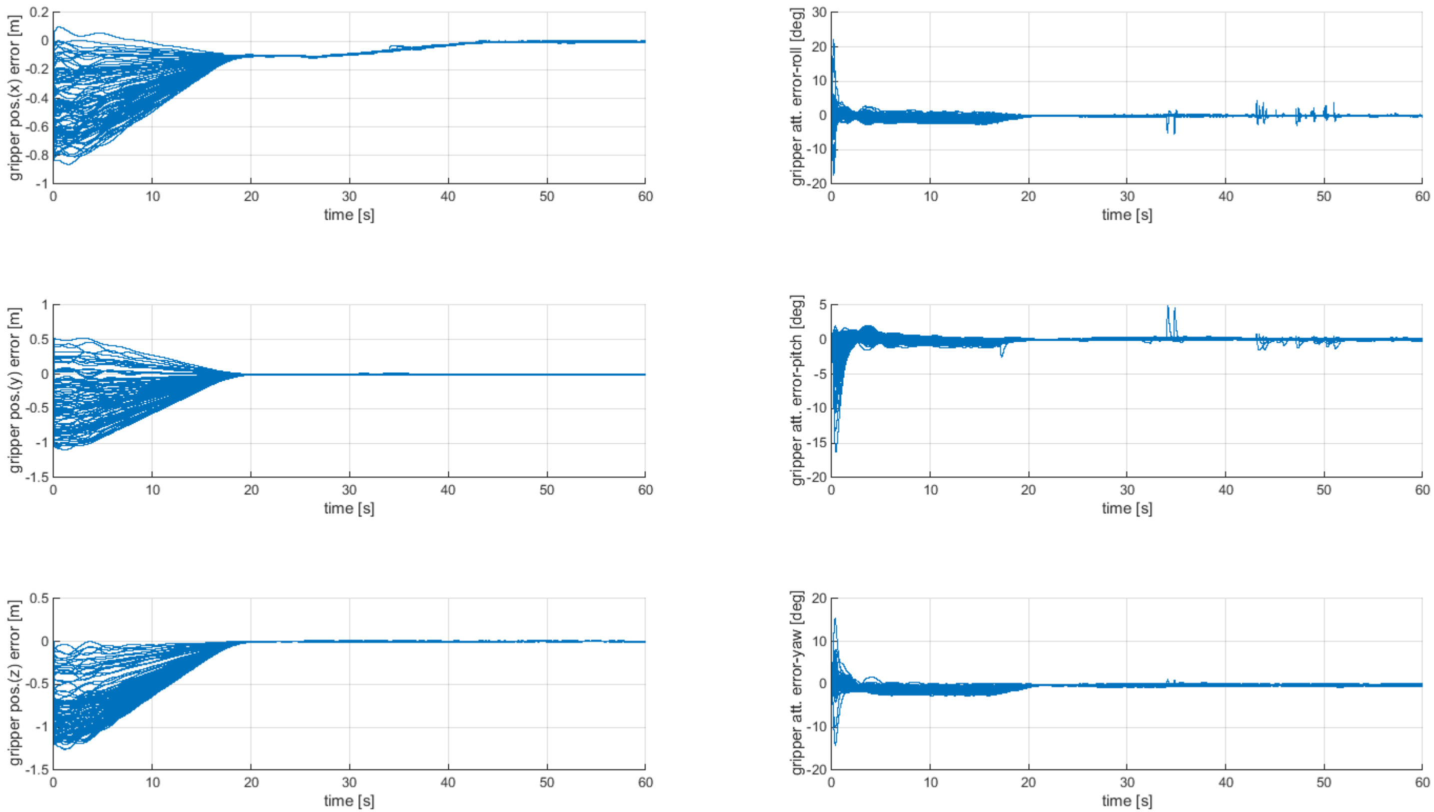


Reach Phase MC, gripper performance (Hinf controller).



Reach Phase MC, gripper performance zoomed (Hinf controller).

RESULTS (MONTECARLO)



Reach Phase MC, gripper performance. (non-linear compliant controller)

RESULTS AND CONTROLLERS COMPARISON

Monte Carlo test campaign:

- **Synchronisation phase** (only H∞ robust control):
  - The obtained Control errors are **within specifications**
- **Reach phase** (both H∞ robust controller and non-linear compliant controller):
  - Both controllers behave **similarly**, with the nonlinear compliant controller having tighter tracking in pointing accuracy
- **End-effector performance:**:
  - Position and pointing accuracy requirements **met** by both controllers
  - Velocity and angular rate accuracy requirements are **overpassed** by both controllers, with lower error mean value for the H∞ control (over Monte Carlo test campaign).

	Synch. phase	Reach phase	
	H_∞	H_∞	Nonlinear Compliant
Position [m]	0.067±0.028	0.023± 0.008	0.026± 0.011
Velocity [m]	0.006±0.002	0.002± <0.001	0.001± <0.001
Pointing [deg]	1.544±0.619	0.318± 0.153	0.105± 0.077
Angular rate [deg/s]	0.155±0.089	0.075± 0.041	0.114± 0.047

End-Effector Performances		H_∞	Nonlinear Compliant
Position [m]	X	-0.001±0.004	0.004±0.003
	Y	0.002±0.005	0.005±0.003
	Z	-0.001±0.004	0.003±0.002
Velocity [m]	X	0.001±0.003	0.004±0.003
	Y	0.001±0.003	0.005±0.003
	Z	-0.001±0.002	0.005±0.003
Pointing [deg]	X	-0.016±0.105	0.120±0.084
	Y	-0.033±0.140	0.086±0.054
	Z	-0.015±0.293	0.182±0.113
Angular rate [deg/s]	X	0.011±0.073	0.520±0.335
	Y	-0.004±0.098	0.286±0.217
	Z	0.029±0.191	0.434±0.314

RESULTS AND CONTROLLERS COMPARISON

- **Rigidization phase**:
  - The achieved **joint position error** for the H_∞ robust controller is 60% of the one for the compliant controller case.
  - For **joint velocity**, the error achieved for the H_∞ robust controller is 21%, of the one for the compliant controller case
  - Probably, better results can be obtained (future work) for the non-linear compliant control by a more adjusted tuning of the position gains in case a specific requirement for the joint positions is given.

Rigidization	H_∞	Nonlinear Compliant
Angle [deg]	1.618±0.809	2.710±1.169
Angular rate [deg/s]	0.016±0.013	0.078±0.030
Initial angular velocity [deg/s]	0.14±0.20(1σ) (Max=3.02)	(1,1,1,1,1,1,1)
Maximum torques around the actuation axis (z) for all the 7 joints [Nm]	(3.87, 12.23, 3.42, 29.80, 12.28, 8.11, 28.10)	(10.94, 12.89, 19.83, 50.10, 17.16, 23.32, 41,45)
Simulation time[s]	120 s	120 s

- **Stabilization phase:**
  - Requirements (ENVISAT case) are comfortably met

Stabilization		H_∞
Angular rate [deg/s]	X	-0.023
	Y	0.006
	Z	0.013

CONCLUSIONS

COMRADE project has currently finalized the Model-in-the-Loop (MIL) level validation phase with successful results and will now enter into the Processor-in-the-Loop (PIL) and HW-in-the-Loop (HIL) validation level.

From MIL-based design/validation phase:

- **Approach/synchronization phase** has considered robust **H∞ 6DOF** controller over a rigid body with sloshing and flexibility (solar arrays, stored robotic manipulator) effects as main perturbations.
- **Reach, capture and rigidization phase** has considered a dual approach and implementation (both controllers have demonstrated to be valid options with some better performance results obtained for the first one):
  - **Robust H∞ 13DOF** controller over a multi-body system composed by the spacecraft platform plus a robotic manipulator with 7DOF (and grasping/re-fueling end-effect at the end).
  - A **compliance/impedance 13DOF** controller over the same multi-body system as for the robust H∞ controller.
- **Stabilization/detumbling** phase has considered robust **H∞ 3DOF attitude controller over the full composite** (chaser S/C + target S/C + rigidized robotic manipulator joining both vehicles) with sloshing and flexibility effects as main perturbations.
- Advanced **FDA/FTC techniques** have been also considered as an additional Failure Detection and Accommodation layer on top of the nominal control design.

THANK YOU

www.gmv.com

gmv BLOG