ESA Developments on GNC Systems for Non-Cooperative Rendezvous

Jesus Gil and Guillermo Ortega
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Introduction

Rendezvous and Docking Heritage

- Rendezvous and Docking (RvD) in space between two objects (chaser and target)
  - Both objects have sensors, actuators and auxiliary equipment that work hand in hand to ensure safe RDV
  - Both objects have been designed with the intention that both shall make a particular physical connection (proper docking ports)

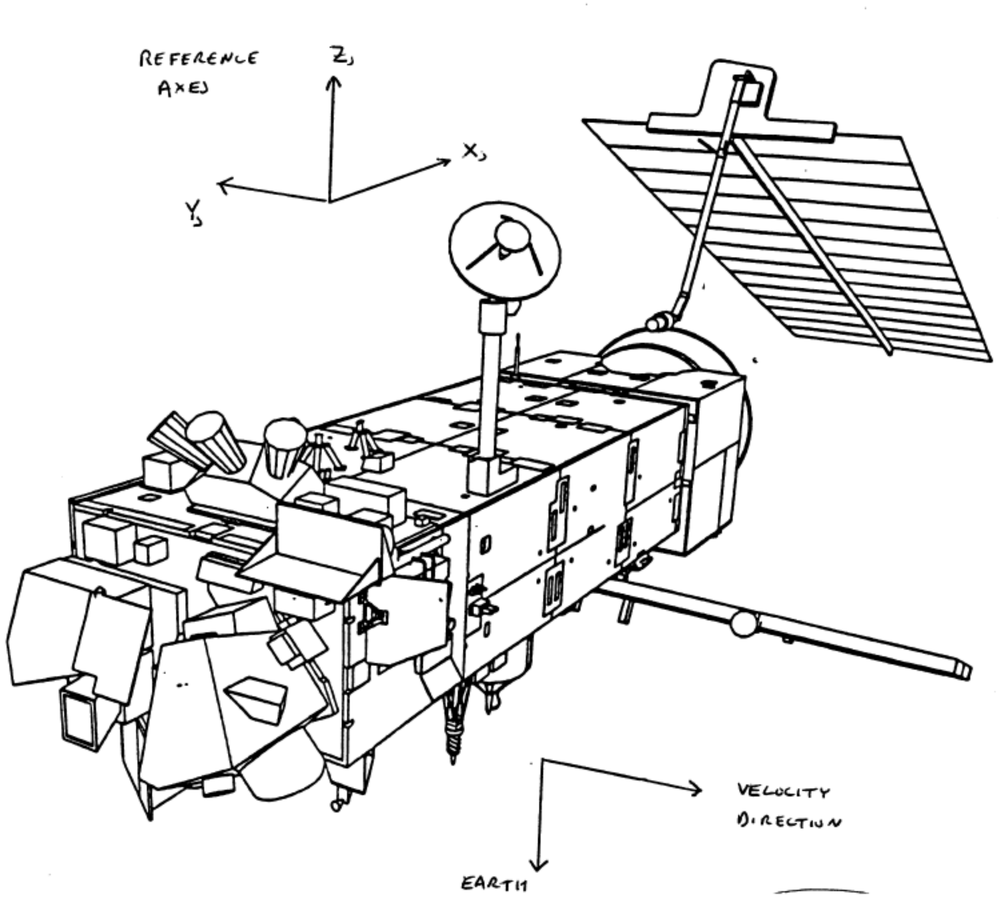
ATV RV: *Fully Cooperative*

Relative GPS: Requires GPS and ISL

VDM & TGM: Requires optical targets

Un-cooperative Rendezvous @ ESA

- Non-cooperative rendezvous
  - Target does not provide any aids for rendezvous sensors
  - Target orientation is not controlled
  - Target motion not known accurately

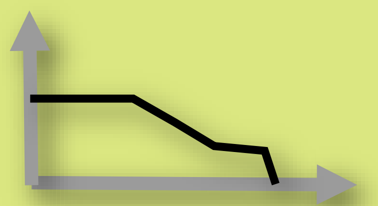


Components of GNC techniques and technologies

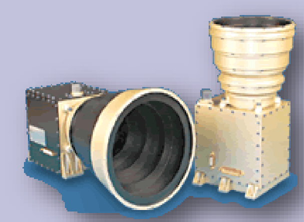
Mission Vehicle Management (MVM)

Guidance, Navigation, and Control (GNC)

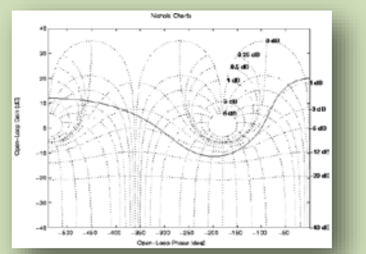
Guidance (G)



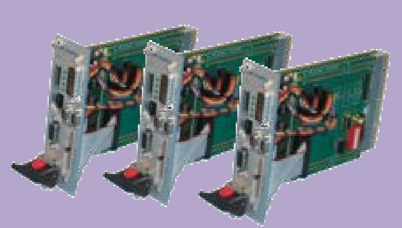
Navigation (N)



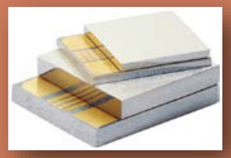
Control (C)



Failure, Detection, Isolation, and Recovery (FDIR)



Heath Monitoring (HM)



Applications

clean space

Future Mission Architectures needing Rendezvous with Uncooperative Targets

Current Status of GNC systems for Rendezvous with Un-cooperative Targets

	Current TRL	ESA missions	Comment
Active Debris Removal	3	e.Deorbit	In Phase B1
RDV with incapacitated GEO	4	ConeXpress	Till phase B2
Asteroid rendezvous	3	AIM	In Phase A/ B1
Comet rendezvous	9	Rosetta	In operation
Sample Return	3	Mars/Phobos Sample Return	TBC

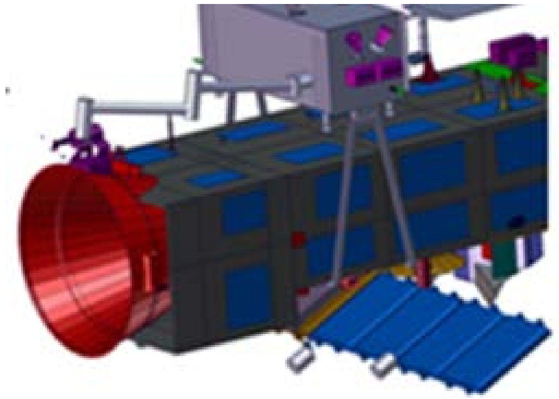
System Options for ADR

Debris Mitigation
- Re-orbit to >2000 km
- De-orbit to <600 km
- Controlled re-entry

Propulsion
- Chemical (CP)
- Electrical (EP)

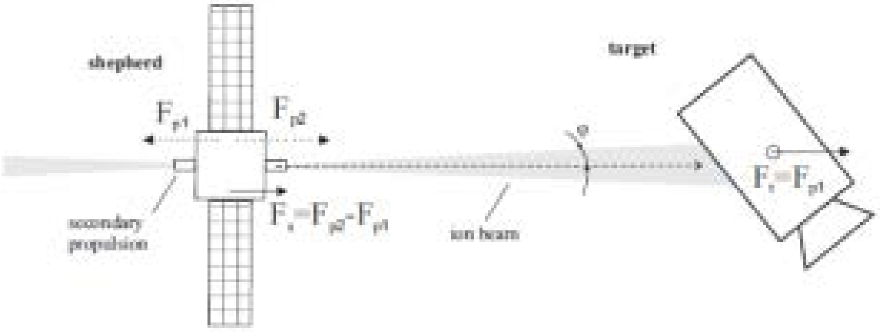
Capture techniques
- Others (harpoon…)
- Net
- Clamping mechanisms
- Robotic arm
- Ion-beam shepherd

Clamping mechanisms

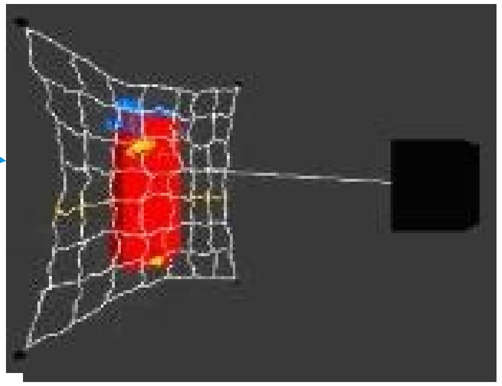


Robotic arm

Ion-beam shepherd

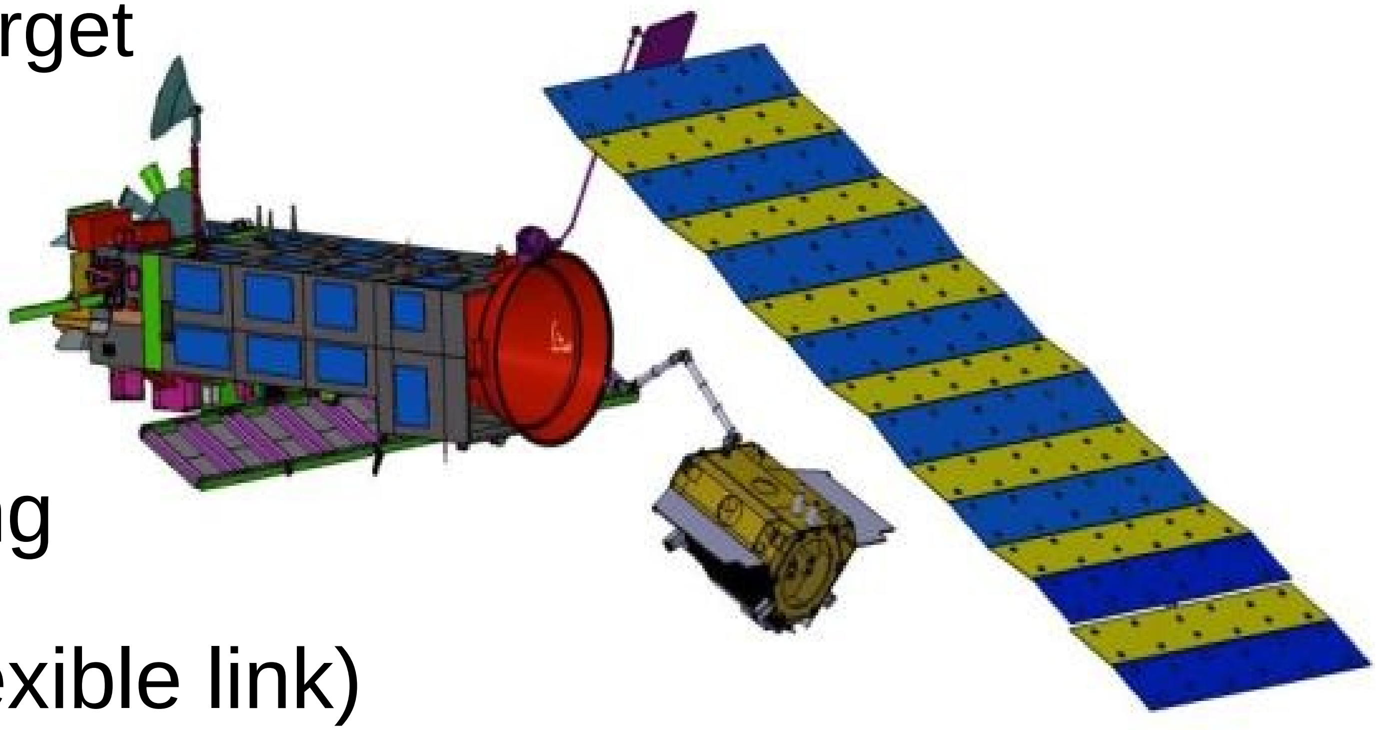


Net



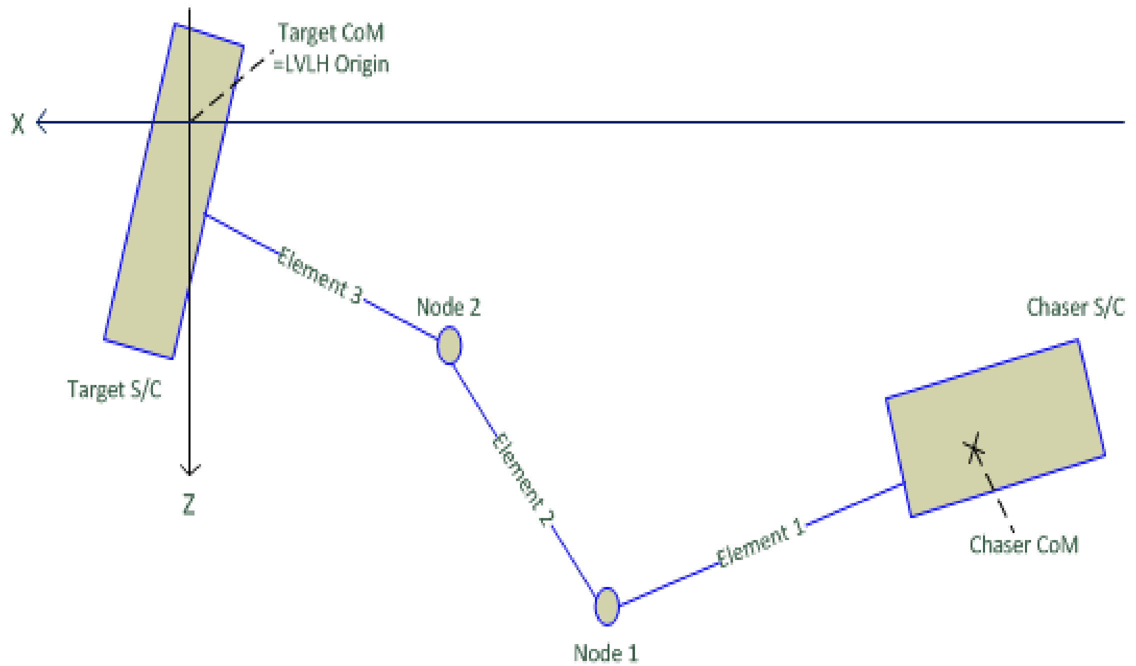
Robot Arm & Clamping Capture GNC challenges

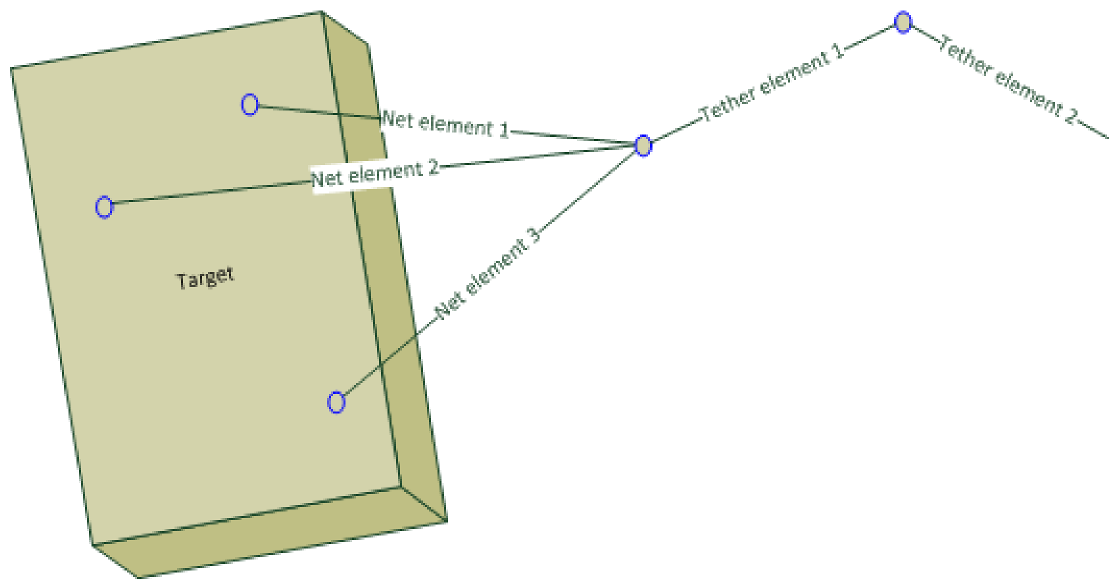
- Approach Target
  - Measure relative pose wrt uncooperative target
  - Match spinning / tumbling target
  - Avoid Target obstacles
- Grab target
  - Accurate gripper positioning
  - Control of Chaser+arm (flexible link)
  - Apply force & torque to the mated Chaser-Target



Net & Tether Capture
GNC challenges

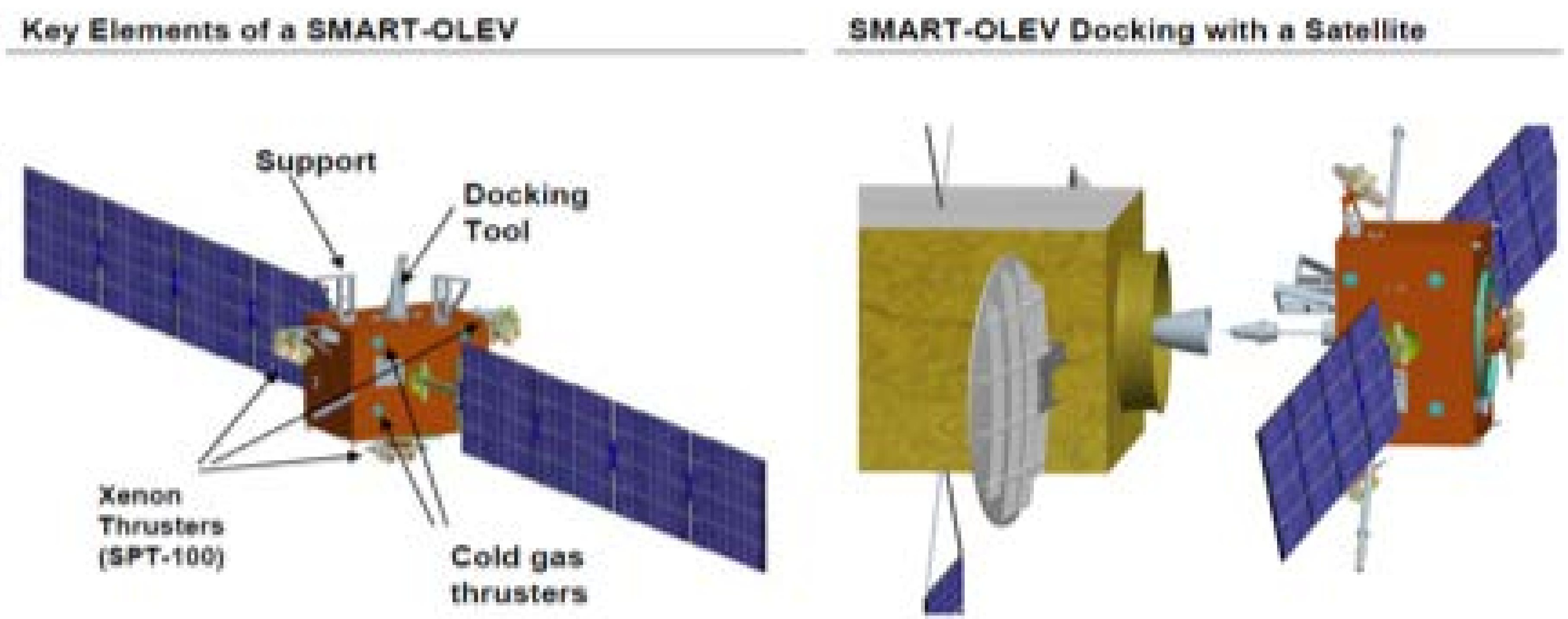
- Elastic tether
  - Non-linearities (no tension when slack)
  - Complex motion, modelled by multiple nodes / connection points
- Control of relative motion to avoid collision
  - Warping around target
  - Relative motion after burns (input shaping, pre-tension)

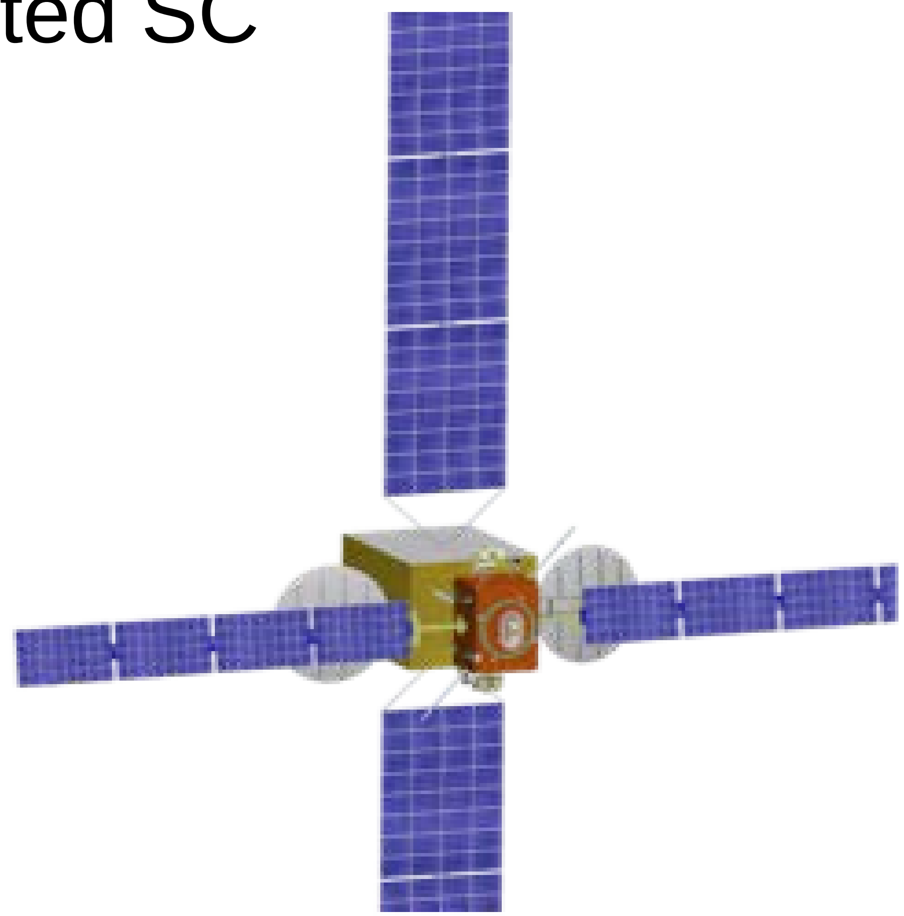




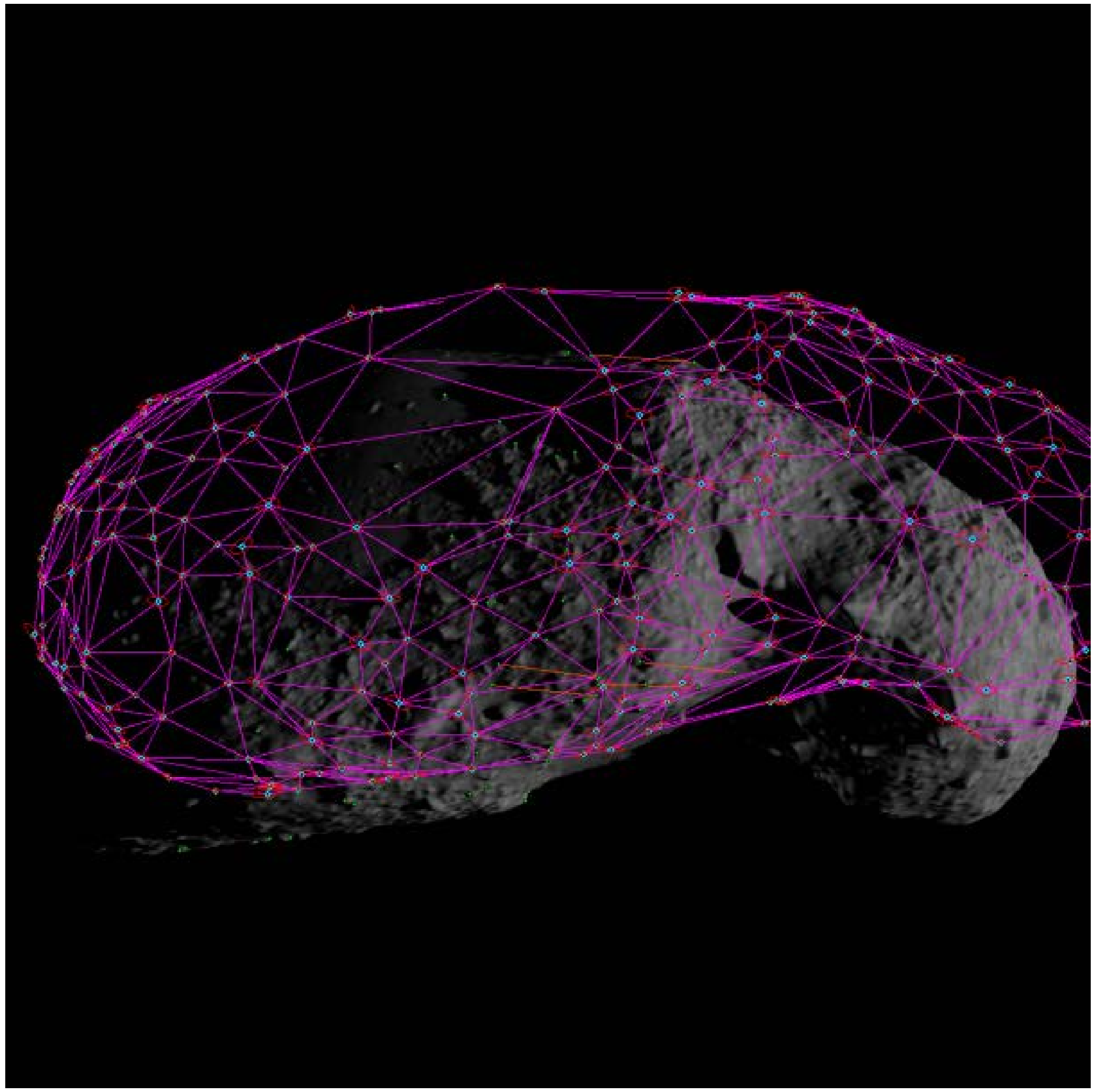
Rendezvous with incapacitated GEO telecomm satellites

- Extension of life for GEO telecomm satellites (or graveyard orbit)
  - Electric propulsion $\Rightarrow$ GNC autonomy for transfer
- Vision-based GNC (stereo) target apogee nozzle (R-bar)
  - No telecomm interruption, control of mated SC





Proximity Operations around Small Bodies



- Strongly perturbed, uncertain dynamics
  - Strong impact of GNC errors
  - Optimal control, predictive-impulsive
- GNC autonomy
  - Reduce operation costs
  - Mandatory for D&L
- Vision-based navigation
  - Unknown feature tracking (relative navigation)
  - Landmark matching (absolute navigation)

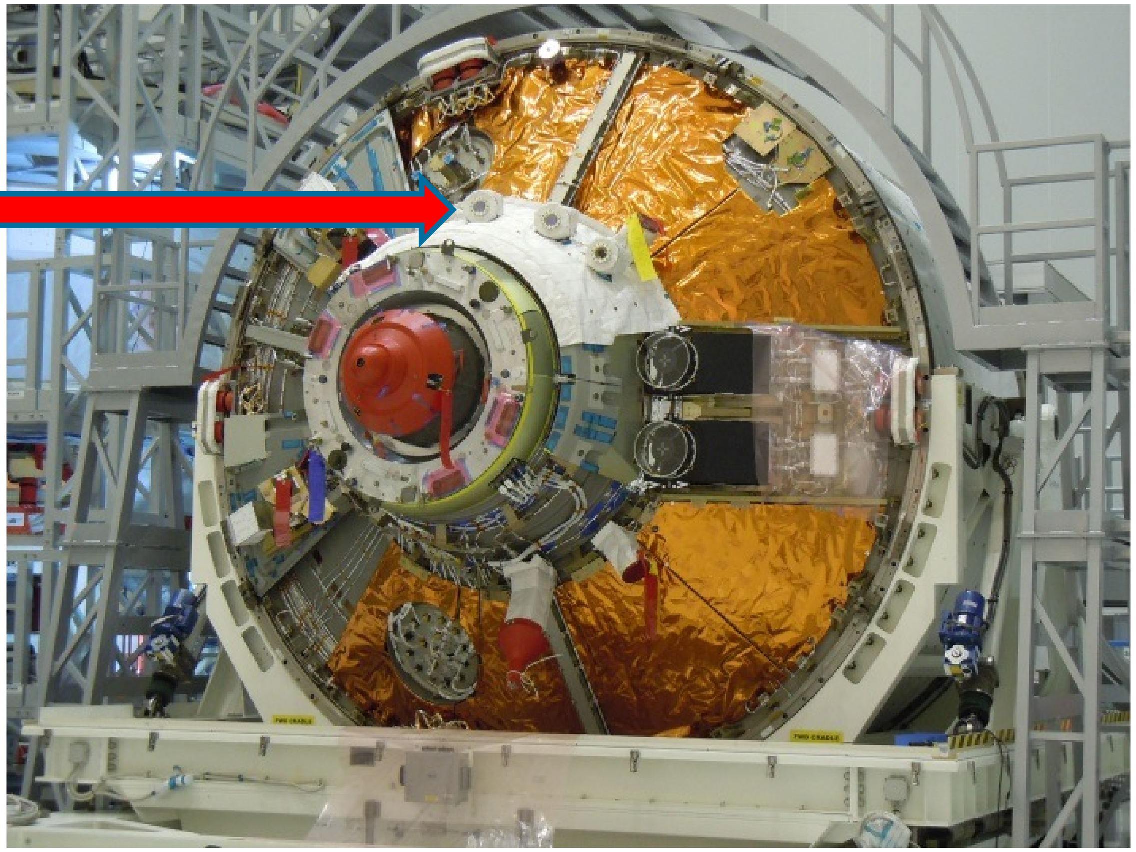
Developments

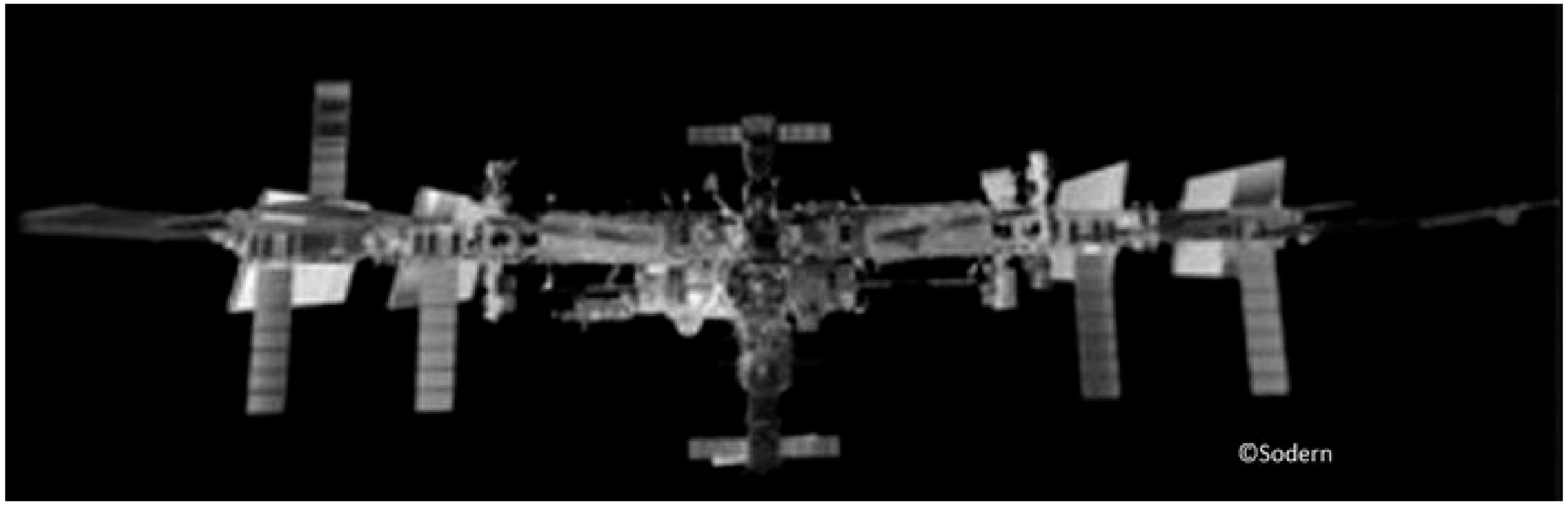
LIRIS ATV-5 GNC Flight Experiment

- Sensor experiment in preparation for non-cooperative RDV GNC system
- Simultaneous image capturing using TIR, Visible and LIDAR sensors
- Capturing range from 70 km down to docked position
  - Lidar only from 3 km
- Validation against flight

  sensors VDM and TGM

  and ATV state vector





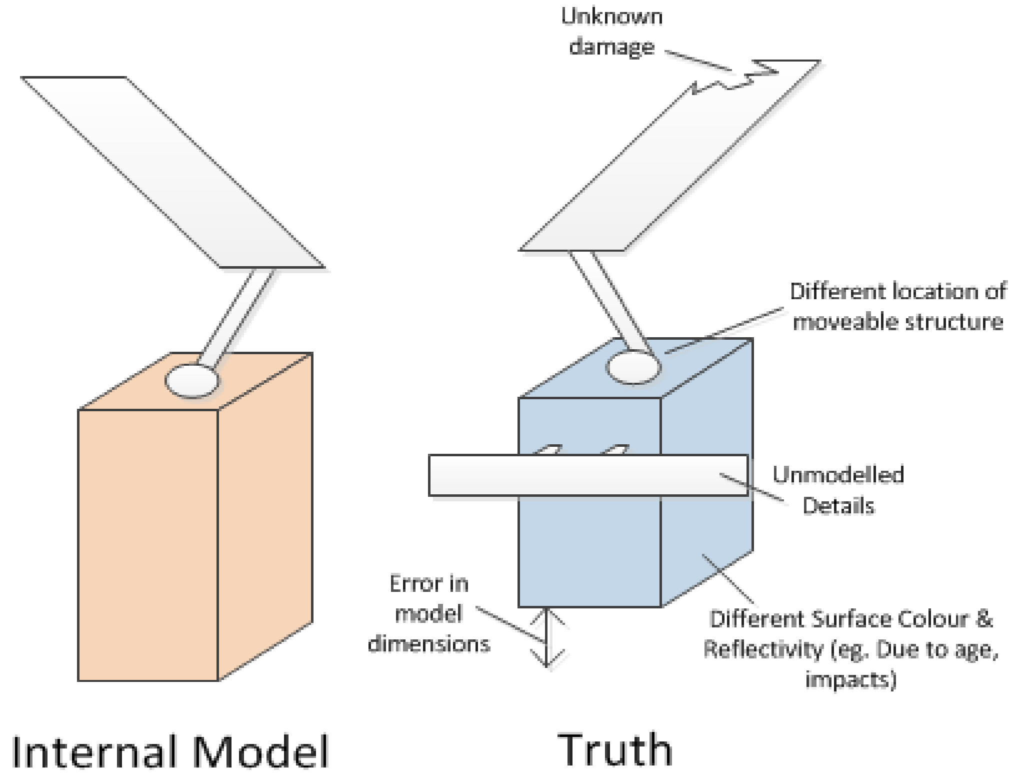
Current GNC technology activities

GSP	TRP	GSTP	NPI
Investigation of active detumbling solutions for debris removal	Advanced GNC for ADR	ADR Image Recognition and Processing for Navigation	Bearings-only Guidance and Navigation for In-Orbit Rendezvous
PRISMA Irides experiment	Multi-Spectral sensor for relative navigation	IR camera breadboard	Infrared based relative navigation and guidance for active debris removal
	GNC using clamping mechanisms		
	Assessment of IR and UV for navigation		

Image Processing (IP) Developments

- Uncooperative Target:
  - fast changes of illumination conditions (due to potential target rotation and revolution around Earth)
  - need to track complex shapes with highly reflective materials and textures of the target debris
- IP techniques need to solve for ambiguities linked to symmetry (e.g. symmetric solar arrays)
- Image processing techniques are required:
  - 3D shape reconstruction from 2D images
  - Visible Camera, IR Camera
  - LIDAR, Stereoscopic imaging, mm-wave Radar
  - Model-based relative pose estimation
  - Real-time processing

- IP algorithms must account for "Deformable" Target
- Damaged Target
- Movable sections (eg. Solar panels)
- Incorrect / old model of Target
- Still need pose estimates in real-time



Investigation of active de-tumbling solutions for debris removal

- Identify the various classes of tumbling objects, investigate and trade for each class the possible de-tumbling strategies
    - Evaluate their impact at system level, taking in particular into consideration the interfaces chaser/target, the operational aspect, develop models of a composite, the GNC design impacts, the propellant cost, the impact on the overall debris removal duration, the required technologies development
- Estimate the target motion and control the non-cooperative formation
- Design and demonstrate the performance of a modern robust control type chaser GNC system for one of the classes (to be agreed by ESA) and establish its boundaries of applicability

Multispectral sensing for relative navigation

- Asses, in a bottom-up approach, the potential use of near IR and near UV wavelengths for relative navigation sensing
- Review existing space-qualified detectors technology which could be used for such purpose and their response in the identified spectral bands, thanks if needed to specific bandpass filters
- To propose a preliminary architecture with the aim to design a multispectral sensing for relative navigation
- Main focus is ADR but other potential applications are considered

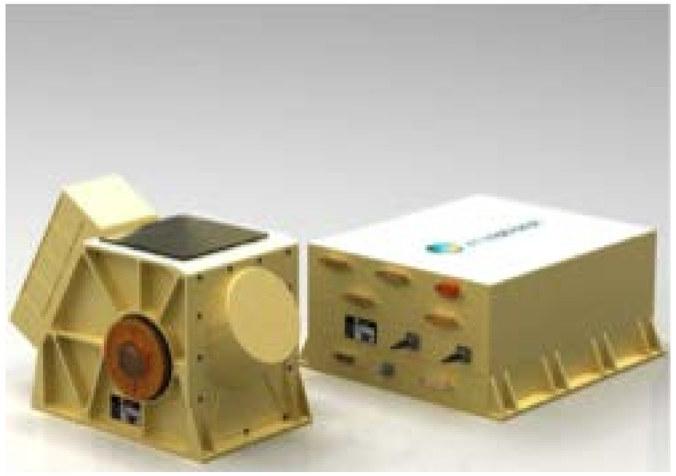
Future Activities

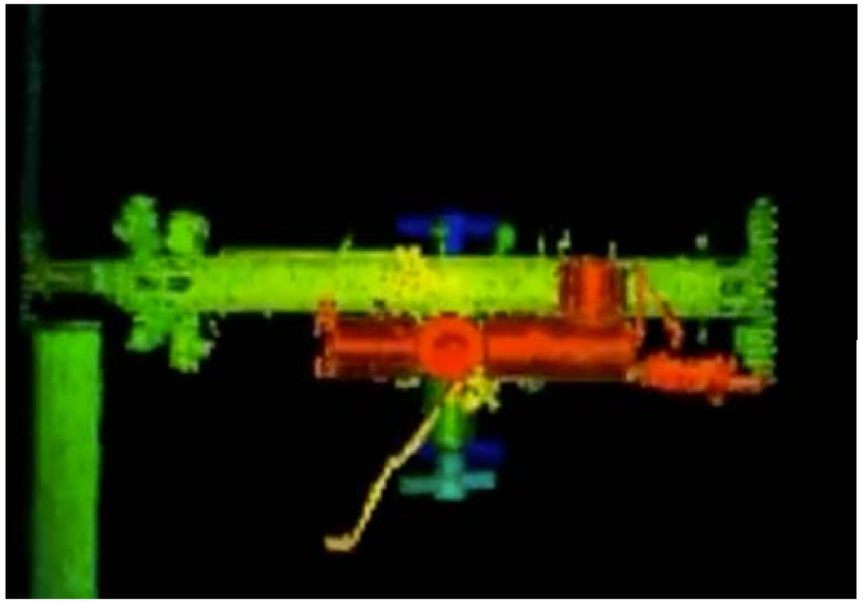
Matrix of upcoming GNC activities

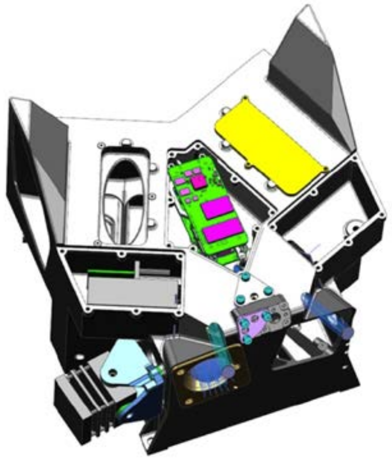
GSP	TRP	GSTP	GSTP
Assessment Toolbox of On-Board and Ground Flight Control Systems for Optimal Mission Cost and Performance	**COntrol and Management of Robotic for Active DEbris removal (COMRADE)**	**GNC design and performance validation for active debris removal with FLEXIBLE capture**	On-board real time trajectory generation
	Adaptive Flight Guidance and Control Systems with Reconfiguration	GNC performance analysis and verification using the Taylor differential algebra DAST toolbox	Integrated Health Monitoring Systems Demonstrator Extension
	Preliminary Design and Development of an Avionics prototype for Nano and Micro-Launchers	**Breadboard of a Multi-Spectral Camera for Relative Navigation**	AOCS aNd GNC ESA Lightweight prototyping Assembly (ANGELA)
	Future navigation concepts at small bodies	**GNC design and performance validation for active debris removal with RIGID capture**	Efficient techniques for orbit determination and manoeuvre estimation using different data sources

Novel/Updated GNC sensors

- Heritage from the 2015 ATV-5 new sensors experiment
- Infrared (IR) and Ultraviolet (UV) sensing technologies
- Miniaturized LIDAR
- Small Integrated Navigator
- Hybrid navigation: GPS + IMU

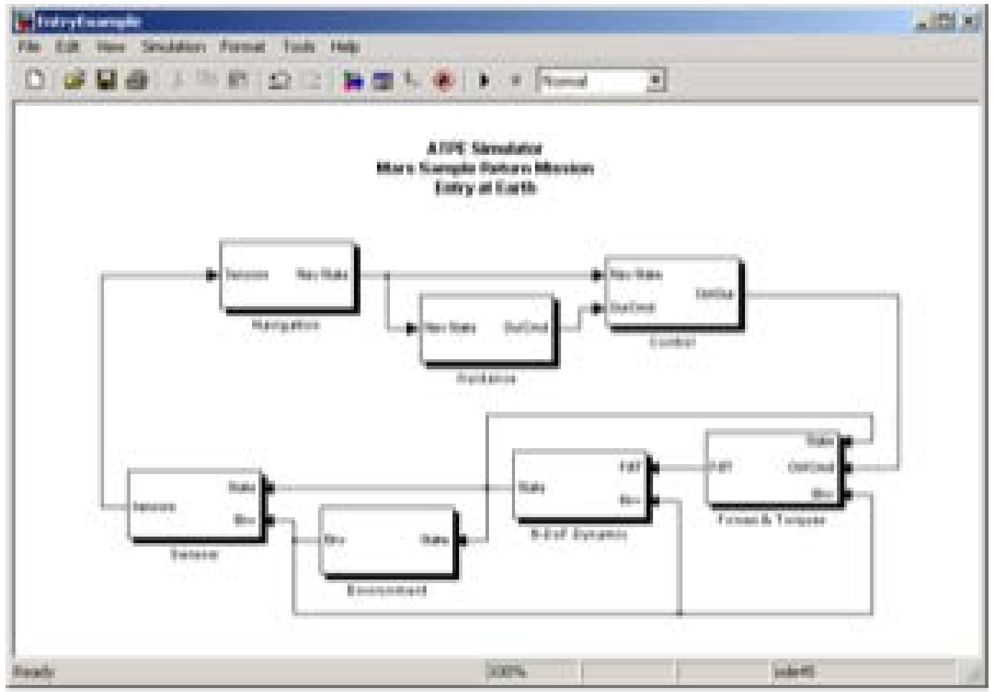






GNC model-based design

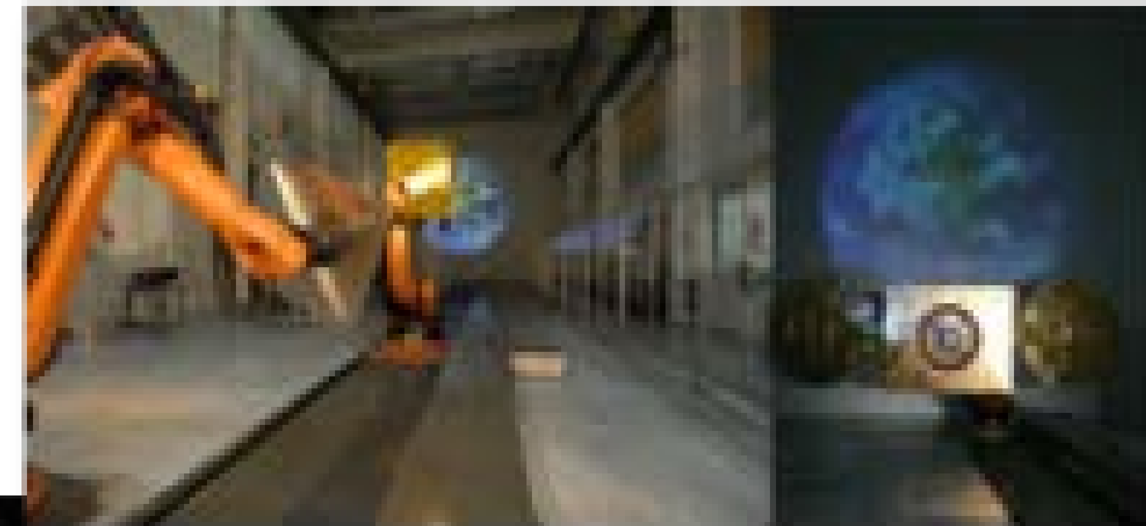
- Model based design approach and auto-coding
- Modeling of GNC algorithms as well as equipment, dynamics and environment
- Tools features allowing straightforward frequency analysis and time simulation
- GNC SW code and verification activities largely automated

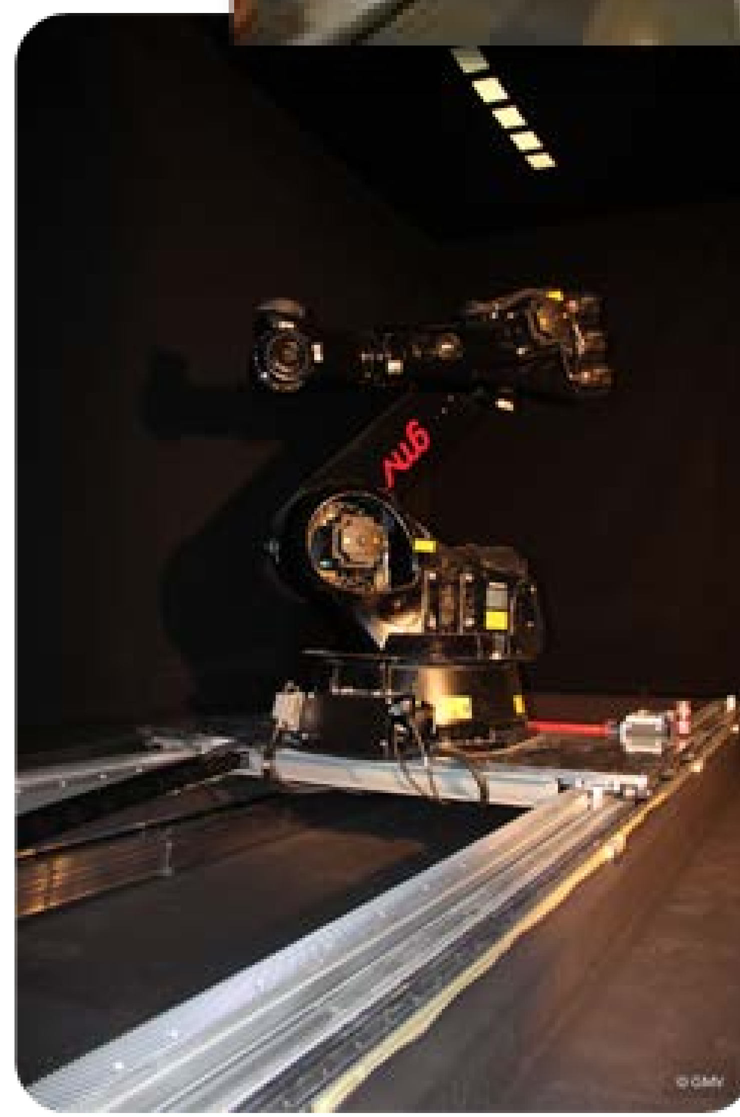


Laboratories

Ground testing and in-flight experiments

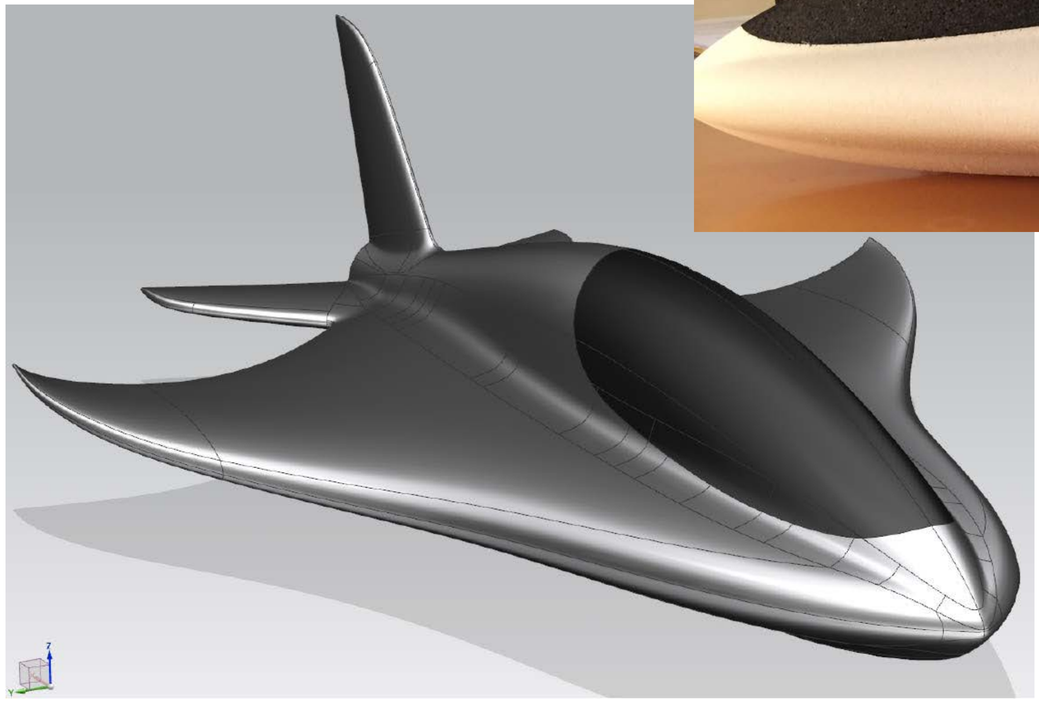
- Extensive closed-loop validation with realistic simulated images
- Scaling in dynamic facility OK to a factor of 10, but not much higher
- In Orbit Demonstration (IOD)





GNC Test Benches and ground demonstration

- Avionics test benches
  - PIL & HIL
- Ground demonstrators: drones, helicopters
- Ground demonstrators: HOMER



ESTEC Laboratories Sub-domains

Materials and Electrical Components Laboratory	01. Materials & electrical components Laboratory	
System & Software Laboratories	02. Concurrent Design Facility (CDF)	
	03. Avionics Systems Laboratory	Software & Simulation
Electrical Laboratories		Data
		Control
	04. Electro-Magnetic Laboratory	EMC
		Antenna measurement
	05. Radio Frequency Payload and Systems Laboratory	Navigation
		Communication
		Remote Sensing
		Radio Frequency and High Power
	06. Power Laboratory	Power System
		Solar Generator
		European Space Battery Test Centre
Mechanical Laboratories	07. Propulsion Laboratory	
	08. Automation and Robotics Laboratory	
	09. Optics & Opto-Electronics Laboratory	
	10. Mechanical System Laboratory	
	11. Life and Physical Science Instrumentation Laboratory	

Control Hardware Laboratory

Sensor Testing Facility
TEC-ECC

The Sensor Testing Facility has been instrumental in providing independent testing with detailed characterisation of performance. The Reaction Wheel Characterisation Facility RCF is now in the test centre

GNC Test Facility
TEC-ECN

Composed of a vision-based navigation sub-facility VISILAB, a Processor-In-The-Loop PIL avionics sub-facility PIL, and the contribution to the Orbital Robotics and GNC laboratory

Missions, Requirements and Experiments in the GNC Test Facility

Missions	Requirements	Experiment/Simulation
Active Debris Removal, PRISMA IRIDES	☐ Robotics: Active debris removal target capture. Active debris removal target-chaser compound de-orbitation. ☐ GNC: Close approach guidance on R-bar and V-bar. Final translation with a forced motion to mate with the target. High throughput processing data from many sensors to obtain navigation solution for each unit.	☐ Rendezvous and capture of a large debris with a net ☐ Rendezvous and capture of a large debris with a harpoon ☐ Rendezvous and capture of a large debris with a robot arm or tentacles
PHOOTPRINT, AIM	☐ Robotics: robotic sampling tool and container. ☐ GNC: Descent and landing trajectory with high accuracy. Control the compound chaser – robotic sampling tool	☐ Descent and landing to Phobos ☐ Touch, grab a sample and go
Landing on the Moon, Landing on Mars	☐ Robotics: NA ☐ GNC: Descent and landing trajectory with high accuracy.	☐ Descent with hazard detection and avoidance ☐ Powered landing
Sample Return in Martian orbit	☐ Robotics: NA ☐ GNC: Rendezvous and capture trajectory with high accuracy.	☐ Search the canister ☐ Rendezvous with canister ☐ Capture the canister

VISILAB

Orbital Robotics and GNC Facility

- TEC-EC/TEC-MM cross-department collaboration addressing common objectives in two distinctive areas:
  - Prototyping and testing of tightly coupled scenarios between GNC and robotics systems (e.g. touch down and sampling systems, spacecraft with robot arms, rendezvous and capture or berthing, etc).
  - Use of the common upgraded laboratory facilities for cross support between the 2 Section's (use of TEC-MMA robots by TEC-ECN, use of TEC-ECN sensors and control systems by TEC-MMA, etc)

GNC Rendezvous, Approach and Landing Simulator (GRALS)

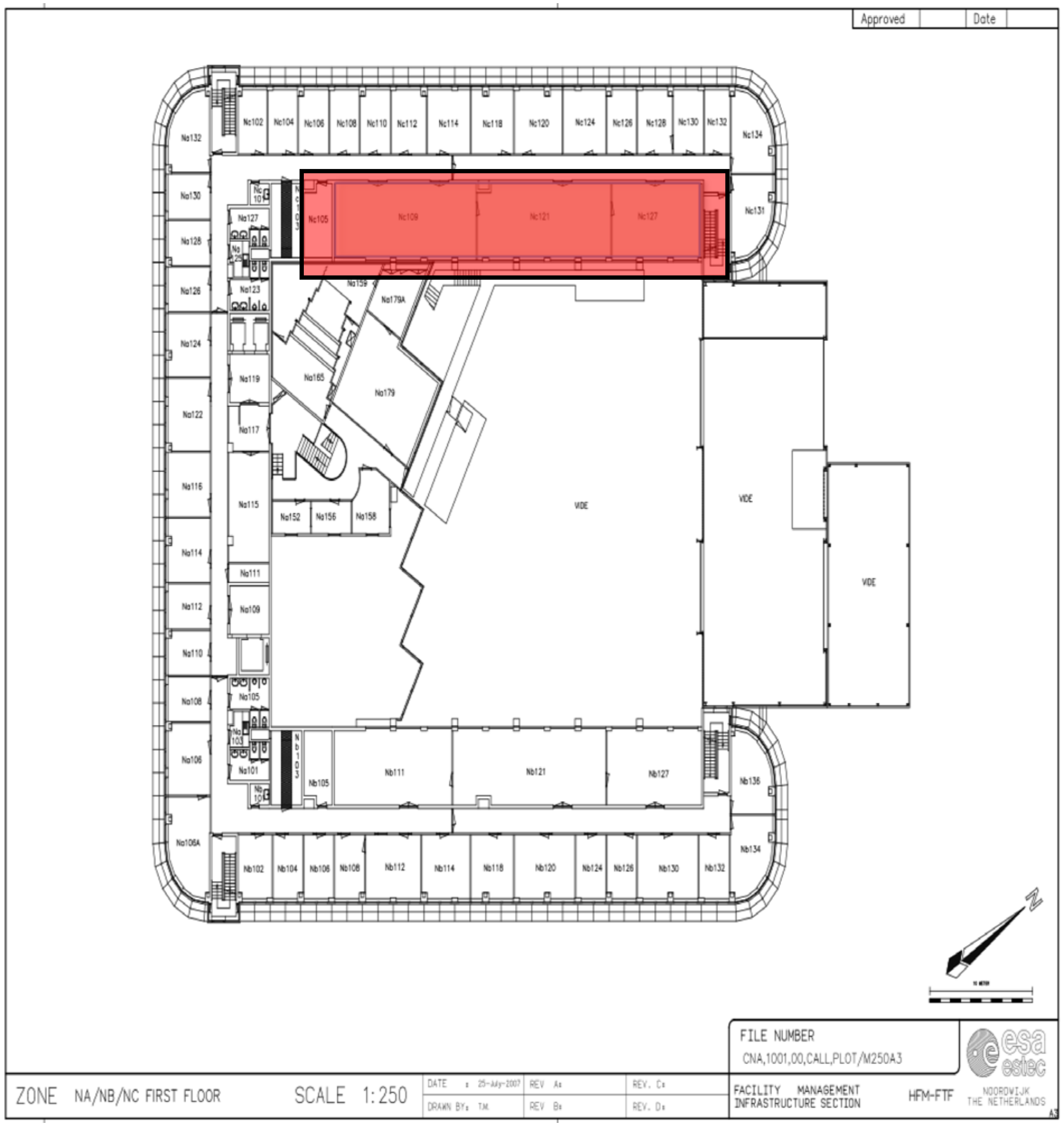
- Laboratory test bed consisting of the hardware of the GNC laboratory, and of a gantry robot from the robotics section to hold a payload and to simulate its movements

- The objective of this upgrade is to combine the elements of TEC-ECN's GNC Laboratory with the robotics test bench of TEC-MMA and to develop the software needed to establish a link between the GNC elements and the robot, such as to create a laboratory test bed to test hazard detection and avoidance experiments in ESA/ESTEC laboratory conditions

Location and availability

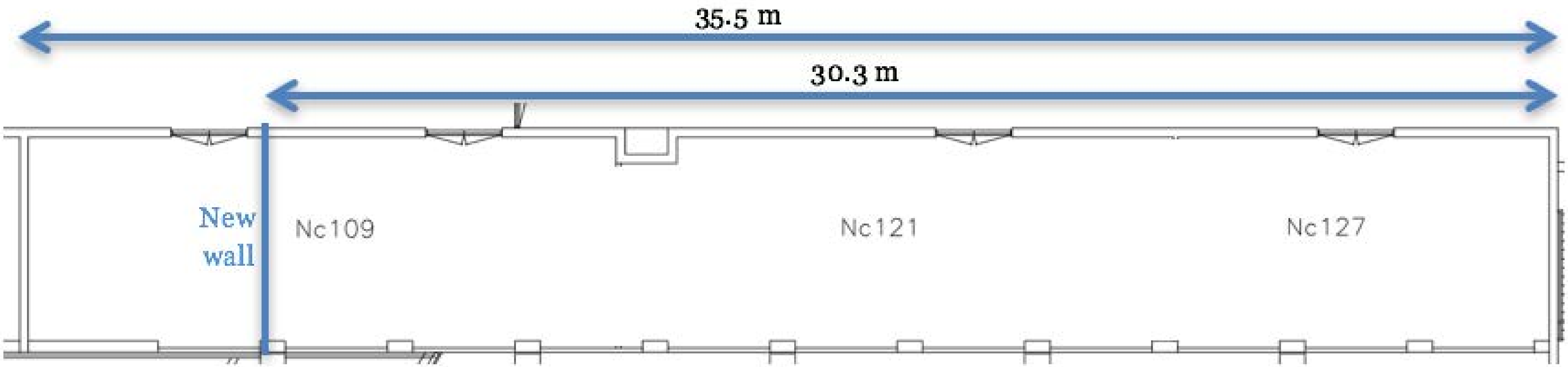
- The GRALS facility is located in the first floor of the ESTEC Erasmus building and comprises 3 joint rooms: Nc127, Nc121, and Nc109

- The robot has been procured and its installation with the rail will be commissioned in Autumn 2016

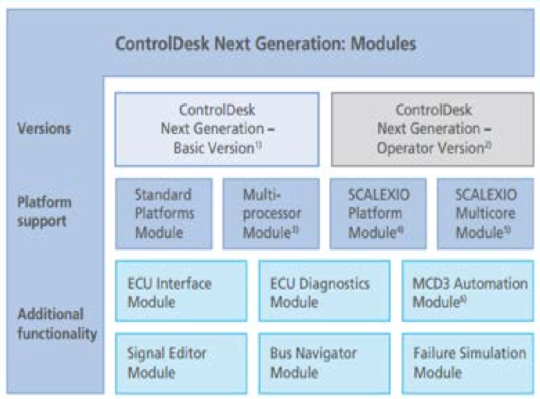
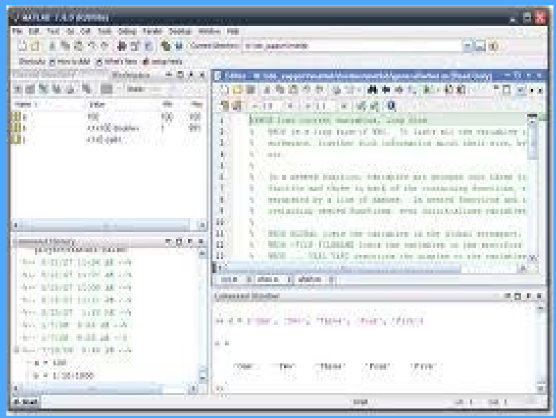


GRALS dimensions

- GRALS has a length of 35 meters and a with of 7 meters. The height of the room is the heigh of all the rooms in the Erasmus building laboratories (3.5 meters)



Software Available at the GNC Test Facility

Type	Photo	Main Features
Control Desk		release is 2013A, introduced in June 2013 by dSpace. • rapid control prototyping (full pass, bypass), Able to perform hardware-in-the-loop simulation, ECU measurement, calibration, and diagnostics, access to vehicle bus systems (CAN, LIN, FlexRay), and virtual validation with dSpace VEOS
TASTE		TASTE stands for "The ASSERT Set of Tools for Engineering" and consists of an open-source tool chain dedicated to the development of embedded, real-time systems. TASTE takes the C-code produced by Embedded Coder from the Simulink canvas and produces binaries that can be executed on the LEON2/RTEMS processor
MATLAB/Simulink	MATLAB SIMULINK	MATLAB, Simulink with Embedded Coder

Conclusions

Improvements for RDV with uncooperative target for ADR

- Improve the navigation estimation function for robust, accurate relative pose until capture
  - Improved sensors working under all/most illumination & geometrical conditions (Sun/Earth dazzling)
  - Fast, reliable, accurate IP (algorithms & HW)
- Advanced control for complex multi-body systems
  - Synchronization, capture, stabilization, burn, post-burn
- Representative ground testing facilities (e.g. TIR)
- In-flight experiments

Thanks for you attention

Matrix of upcoming GNC activities

TRP	ARTES	MREP #2	Ariadna
Compact Reconfigurable Avionics- Smart AOCS & GNC Elements	Assessment of avionics systems development for telecommunication missions using 3D printing	Vision-based navigation camera EM for PHOOTPRINT including image processing	Onboard DA state estimation
	Low cost generic FDIR development for telecommunication missions		
	Megaconstellations CONOPS testbed/emulator		
	Optimal Deployment of Mega-Constellations using Quantum Computing Technology		