

Guidance, Navigation, and Control of In Orbit Assembly of Large Antennas - Advances and Results from the IOANT Project

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ABSTRACT

The (ESA funded) IOANT project develops and validates an autonomous Guidance, Navigation, and Control (GNC) framework for in-orbit assembly of large reflector antennas that exceed current launcher volume constraints. The project addresses the challenges associated with assembling modular structures in space, including significant variations in mass, centroid, and inertia properties, flexible structural dynamics, contact disturbances, and the need for autonomous operations. The project comprises two phases. Phase 1 establishes a complete end-to-end assembly concept involving a Central Module, a Transport Tug, reflector-segment stacks connected through standard interfaces, and a Multi-Arm Relocatable Manipulator. A unified GNC was developed, integrating event-driven autonomy, model predictive translational guidance, system identification, and robust model-based control techniques. Extensive verification and validation, including Monte Carlo simulations, demonstrated performance and robustness under large uncertainties. Phase 2 experimentally validates these concepts using two surrogate ground test-beds and facilities. The Space Robotics Emulator supports planar microgravity experiments for rendezvous, capture, mating, and contact-dynamics control, while the TRACTOR-Beam platform reproduces time-varying inertia and flexible dynamics with hardware-in-the-loop testing. Results provide the first physical validation of IOANT's time-varying GNC concepts, advancing key technologies toward TRL 4/5 and enabling scalable future in-orbit assembly missions for large antennas and modular spacecraft.

1 Introduction, Motivation and Approach

Enhancements in the communications capacity of future satellites can be achieved by increasing the reflector surface area, producing narrower beams [1, 2]. A natural solution to the limitations imposed by a single launch is to split the payload into several launches and then perform in-orbit assembly (IOA) operations. In-orbit assembly presents several benefits. It allows the construction of structures that do not fit into a single launcher, even opening the door to structures that could not be created on ground because of the limitations imposed by gravity. It can also increase the longevity and reliability of missions by replacing faulty, damaged, or outdated elements [3]. There are also potential cost savings by reducing the mass required for protection and deployment mechanisms and reducing ground testing.

However, it presents several challenges being studied, both from the system and Guidance, Navigation and Control (GNC) perspectives. From the system point of view, such a mission requires multiple vehicles to transport

and assemble modular segments; there is mechanical contact between several elements, which requires the use of manipulators and locking and interlocking mechanisms [4, 5], introducing disturbances during the assembly process. The main GNC challenges appear in Control; the structures experience large changes in physical properties as the assembly progresses, particularly in the mass-inertia (MCI) properties and the flexible properties. The developed control system needs to take those variations into account and be robust to uncertainties.

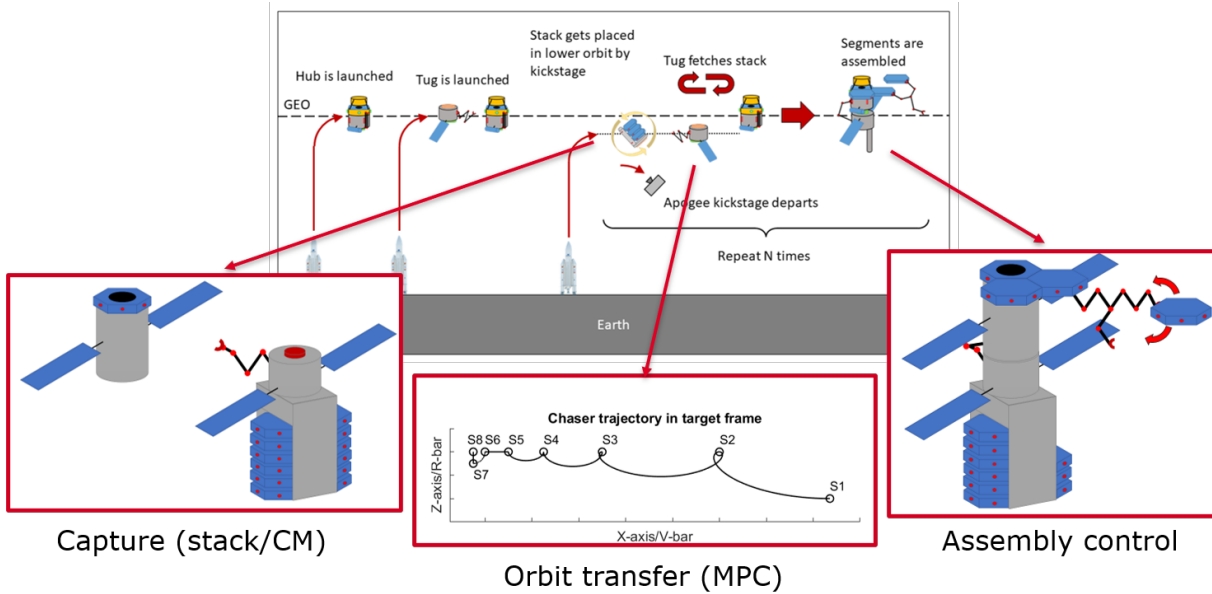


Figure 1 Mission scenario, system, and concept of operations in the IOANT study, based on a multiple arm robot such as MIROR [5].

The IOANT project is an ESA funded project [6] through the ARTES programme [7] to develop and validate an autonomous Guidance, Navigation, and Control (GNC) framework for In-Orbit Assembly (IOA) of large reflector antennas, and study the associated main challenges to provide an integrated solution for a proposed mission concept for assembly, Fig. 1. The activity was structured into two phases, Fig. 2:

- **Phase 1** consisted in the definition of a feasible end-to-end in-orbit assembly scenario, including vehicles, mechanisms, and interfaces. A complete and versatile GNC solution was developed and validated using an integrated, coherent, and incremental detailed design, validation, and verification approach.
- **Phase 2** advanced the GNC solution by designing and performing end-to-end proof of concept tests in a ground facility developed for the activity, using a scaled-down version of the scenario studied in Phase 1.

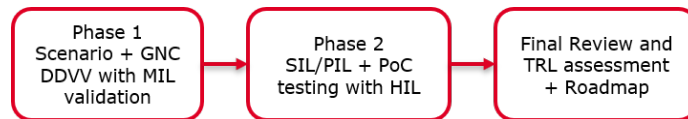


Figure 2 Project phases logic for the IOANT project: concept and framework, followed by experimental validation.

These phases already provide the main steps of a waterfall Design, Development, Verification and Validation (DDVV) process [8], and the approach considered individual and incremental contributions, development and validation tasks. By following the such DDVV approach, efficient re-use of all work and models developed during early activity tasks were applied to later coming tasks (e.g. smooth integration of models in the non-linear simulator, smooth autocoding, etc.). Instrumental to these objectives, and objectives on their own were:

- 1) to establish the needs and characteristics for large orbital antennas through survey – and hence a perimeter for the IOA system and a representative End-to-End scenario for which to tailor a flexible solution.
- 2) to define an IOANT solution – mechanisms, interfaces, GNC functions – that could be applied to the identified scenario and envelope.

- 3) to consolidate and advance the maturity of the solution, based on heritage, through a DDVV process, which requires accurate modelling, simulation of all its components and testing in a MIL→SIL→PIL (Software-in-the-Loop→Processor-in-the-Loop) toolchain [8]. In parallel the flexible IOA solution was tailored for an experimental End-to-End Proof of Concept test.
- 4) to design, setup, manufacture and breadboard a scaled version of the IOA solution to End-to-End Proof of Concept in an experimental facility which: a) can further the readiness of the solution; b) closes the gaps into some aspects that are not easily simulated (e.g. contact dynamics)

The IOANT activity raised the Technology Readiness Level (TRL) [9] to 4/5 (from 2/3 depending on components).

2 Phase 1 – Study for Full-Scale In-Orbit Assembly Scenario

Phase 1 focused on the definition, development, and validation of a complete GNC framework, Fig. 3, culminating in a comprehensive Model-in-the-Loop (MIL) verification campaign. The main outcomes of Phase 1 were:

- 1) Definition of a complete and coherent in-orbit assembly system concept
- 2) Development of a scalable and robust GNC architecture
- 3) Design of advanced control algorithms addressing time-varying multi-body dynamics
- 4) Establishment of a high-fidelity simulation and validation framework
- 5) Successful demonstration of feasibility through extensive MIL validation

These establish the baseline to transition to experimental validation and technology maturation during Phase 2.

PHASE 1

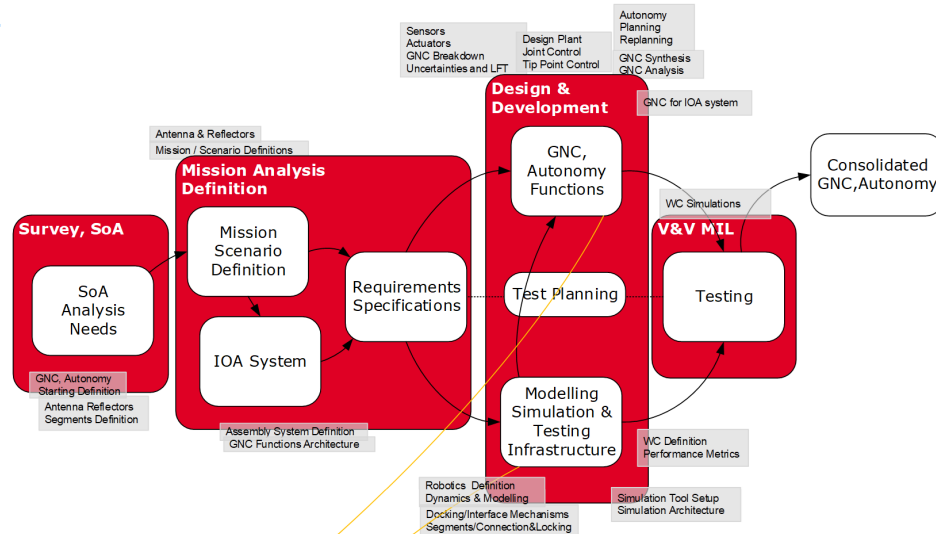


Figure 3 Work flow and tasks during Phase 1 to arrive at the GNC concept and validation with Model-in-the-loop.

2.1 Mission and System Definition

The In-Orbit-Assembly scenario was the result of mission analysis and trade-offs. First, an orbit was selected based on the type of mission, impact on rendezvous operations and payload mass capabilities. From here, an estimation of the available payload per launch and the assembly timeline was provided, and the system (vehicles, components) selected, to arrive at the Concept of Operations (ConOps). The scenario features a central module spacecraft used as central element to build the antenna, with a walking Multi-Arm Robotic Manipulator (MARM), a tug spacecraft that transports elements between different orbits and features a manipulator for mating operations, and stacks of reflect-array antenna elements which need to be assembled to the central hub by means of the MARM, Fig. 1, and standard interfaces for mating operations [4, 5]. The mission sequence follows:

- 1) The launcher injects the spacecraft into a Geostationary Transfer Orbit (GTO) with apogee 250 km below Geostationary Earth Orbit (GEO). This value of 250 km is chosen to be safe under dispersions from the launcher upper stage.

- 2) An apogee kick-stage circularizes the spacecraft.
- 3) The spacecraft (either autonomously or carried by another vehicle) performs a rendezvous sequence to reach the target state in GEO, based on Hohmann transfer, tangential and radial V-bar transfers, finalized by straight line approaches in V-bar and potentially R-bar.

The rendezvous and assembly are divided into 5 different operations:

- 1) Orbital translational operations
- 2) Pre-mating operations, which are common to both the stack capture and the central module capture
- 3) Assembly operations on the central module
- 4) Mating with Stack operations
- 5) Mating with Tug operations, including both capture and separation

2.2 Guidance and Control Design and Implementation

Algorithms for Guidance and Control (G&C) under nominal conditions (without failures) are designed and validated to provide a baseline to which we can compare the impact of the modelled failures, and the recovery strategies in terms of control authority, control performance, and dispersions at the end of the first stage flight. The nominal G&C was validated in the time domain with a Monte Carlo campaign and parametric dispersions with the Functional Engineering Simulator (FES). The focus of the activity was placed in the development of the following G&C algorithms:

- Tug impulsive translational Model Predictive Control (MPC) guidance to transfer the tug between orbits
- Tug coordinated platform-manipulator controllers
- System identification for tug and central module
- Central module attitude control for variation of MCI properties during assembly

Obit Transfer MPC Guidance

The impulsive translational guidance is performed by a convex optimisation-based shrinking horizon MPC algorithm [10], Fig. 4, where impulsive velocity changes are issued at the current time-instant. The algorithm minimizes the total changes in velocity ΔV throughout the remainder of the horizon of the manoeuvre, while penalising the final deviation from the final holding point. The guidance is designed to be capable of:

- 1) Minimizing propellant and energy consumption during the manoeuvres.
- 2) Taking into account actuation, ΔV , or power budget limitations.
- 3) Considering critical safety constraints, including actively avoiding collisions to the target or other objects in the vicinity, passively avoiding the occurrence of collisions due to the natural drift, or escape trajectories.
- 4) Enforcing performance requirements on trajectory design, i.e., making sure that the initial dispersions are corrected towards the end point.

These goals could be met by a single online optimization with a fixed horizon at the start of the covered mission phase, solving the underlying optimal control on-board albeit in open-loop (thus taking into account the state of the vehicle at that particular time but not considering the improvements in navigation that occur when the distance to the target is reduced). Instead a model predictive controller was employed to fully exploit the adaptiveness and robustness that can be provided by such methods. This allows to reoptimize the trajectories and course correct the manoeuvres according to 1) better navigation estimates, and 2) unmodelled effects in the dynamic environment or errors in the previous manoeuvres.

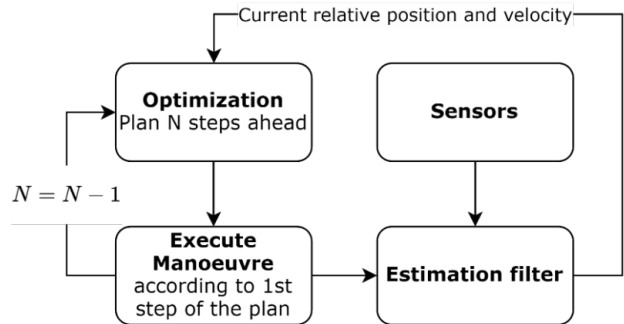


Figure 4 MPC algorithm with receding horizon.

Platform-manipulator Coordinated Controllers

There are three different controllers defined for this system, depending on the task at hand: a joint-space controller, a cartesian space inertial controller and a cartesian space relative controller.

A **Coordinated Joint Space Model – Based PD** was developed to control both the Tug's platform attitude and the manipulator joint configuration considering the parameter uncertainties and/ or the disturbances caused by the solar panel mounted on the platform. The model-based part of the controller employs inverse rigid-body dynamics compensation, where the nonlinear manipulator-spacecraft dynamics are explicitly included in the control law. This reduces nonlinear coupling effects, allowing the feedback PD (or PID) terms to regulate mainly residual modelling errors, disturbances and parameter uncertainties. Moreover, the coordinated formulation explicitly accounts for the dynamic coupling between the manipulator and the free-floating spacecraft, enabling simultaneous control of both subsystems. To develop this controller the system dynamics are derived in a form suitable for control purposes where the model-based controller employs only the rigid-body dynamics. The avoidance of solar panel and/or fuel sloshing flexible modes excitation can be achieved by guidance, by generating a desired acceleration profile using pre-shaping techniques, and/or by selecting appropriate controller gains to achieve a closed-loop response with bandwidth below the lowest estimated resonant frequency of the system flexible dynamics.

The **Coordinated Cartesian Inertial Space Model – Based PD** is focused on the case where the Tug is close to the Stack and a precise placement of the Tug's end-effector is required to grasp the Stack. During this mission phase, the Tug platform uses its Reaction Wheels (RWs) for attitude control, but the Tug thrusters are turned-off for safety, due to its proximity to the Stack. The robotic arm uses the joint motors to control the end-effector pose (position and attitude) in inertial Cartesian Space, i.e., with respect to the Stack. The Cartesian Space controller, is a Coordinated Model – Based Compliant PD controller which also considers the external forces/ moments caused by the contact between the Tug's end-effector and the Stack. This controller is effective for system small disturbances such as those introduced by unmodelled dynamics (e.g., solar panels dynamics) and system parameter uncertainties.

The **Coordinated Cartesian Relative Space Model – Based PD** is used when manipulator needs to relocate the two vehicles relative to each other. Therefore, the end-effector has to move along a particular trajectory, defined in the Tug's base. Also, since this base is not fixed, the Cartesian control law must use the end-effector velocity relative to it (self-referenced Cartesian control). To reduce the resulting contact force between the Tug and Stack and increase the contact time, a controller with compliant behaviour is applied.

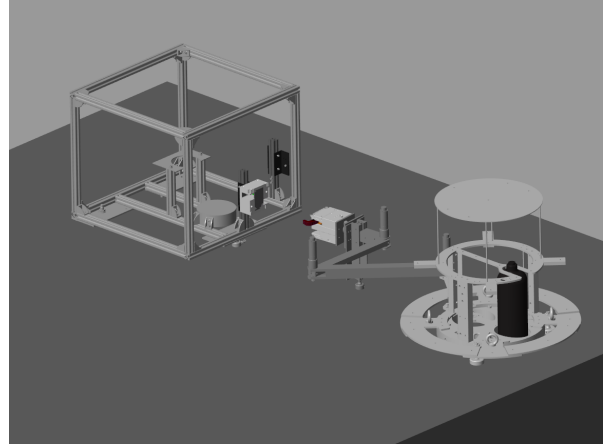


Figure 5 *Simscape [11] modelling for multi-body simulation and contact to support design and experiments for capture and mating.*

System Identification

The Tug system identification is based on Modal Analysis assuming the systems' inertial properties are known to acceptable extent, and the parameters to be identified include the sloshing fuel model parameters (Parametric Identification) and the modal parameters (Modal Analysis) of the flexible appendage (e.g., solar panels). Modal Analysis is used to identify the modal characteristics of flexible elements (e.g., solar panels), such as natural frequencies, damping ratios and modal shapes. The most important of the outputs are the natural frequencies of the studied flexible element. By having a good estimate of those natural frequencies, care can be taken in the system control design so as not to excite them, e.g., by proper selection of the control gains.

Covariance-driven Stochastic Subspace Identification (SSI-COV) is used for Modal Analysis as well [12]. SSI-COV is an “output-only” method, meaning that it does require output measurements only, and not input

measurements (a measurement of the excitation). Moreover, it does not require for the identification process any model of the flexible appendage. The required measurements are obtained by several accelerometers placed on the flexible appendages, providing three-dimensional acceleration measurements of the corresponding points on the appendages.

For the identification of lumped parameters of the central module as it performs the assembly, a different type of identification - Parametric SYSID - must be performed for the system MCI properties and for the sloshing fuel mass-spring-damped model parameters. Based on prior experience, three types of SYSID algorithms were promising: Least Squares (LS) and its variations (especially Total Least Squares - TLS); Kalman Filter (KF) and its variations (such as Extended Kalman Filter – EKF and Unscented Kalman Filter – UKF); and Prediction Error Method (PEM).

Central Module Assembly Control

The attitude control of the central module during assembly operations must: maintain a fixed pointing under disturbances coming from the robotic manipulator performing assembly operations; consider the variation of MCI properties during the assembly, and adapt to changes in inertia; and finally, consider the variation of flexibility properties due to the addition of tiles to the assembly, and the different excitation of flexible modes depending on the position of the robotic manipulator. Such requirements are better fulfilled by an adaptive scheme, scaling the gains with an estimation of the inertia, and updating the bandwidth based on the expected low frequency flexible modes, Fig. 6:

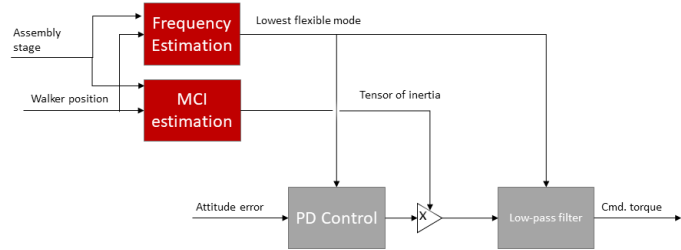


Figure 6 Adaptive architecture for control during assembly, with time-varying inertial and modal frequencies.

- 1) Based on the assembly stage and the walker coordinates on the surface of the antenna, the flexible mode frequency is computed using look-up tables, and the MCI is computed using parallel axis theorem with the added elements and the walker position.
- 2) The frequency of the low-pass filter is a fraction of the lowest flexible mode frequency, and the frequency of the PD is a (smaller) fraction of both, to ensure there is no excitation from the controller bandwidth.

2.3 Model-in-the-Loop Validation and Verification

Phase 1 carries the DDVV up to MIL with integration tests and Monte Carlo (MC) test campaigns to verify the integrity and performance of the GNC system.

Three FES with different level of complexity and size were developed, for testing the different operations considered in IOANT:

- 1) A low fidelity, chaser only simulator to test optimal orbital guidance and GNC transitions, called Orbital Simulator.
- 2) A high fidelity, chaser and target simulator for capture and mating, called Mating Simulator
- 3) A high fidelity, chaser + target simulator for assembly and identification, called Assembly Simulator

The main dynamical effects considered in the simulators are: the flexibility of the antenna and solar panels; orbital dynamics and relevant disturbances (J2,

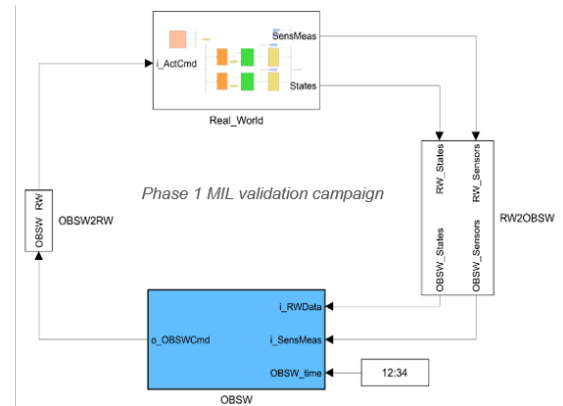


Figure 7 Simulator architecture for Model-in-the-Loop simulations using the validation at the end of Phase 1.

drag, Solar Radiation Pressure); manipulator multi-body dynamics modelled using Simscape; changes to system properties, mainly MCI and flexibility when a new element is attached; and disturbances from robotic manipulators during transport and assembly.

Multiple scenarios were executed, each with at least 100 successful MC instances. For each of the simulators, Fig. 7, the executed campaigns for the **Mating Simulator** were:

- **Manipulator deployment and SYSID:** The manipulator is extended in Cartesian space and then dedicated manoeuvres change estimate the MCI.
- **Mating with Central Module:** The central module is captured.
- **Stack relocation and accommodation:** After capture, the manipulator moves the two vehicles and aligns the interfaces.

For the **Assembly Simulation**, there were:

- **Tile attachment:** One tile is attached, changing the properties of the antenna.
- **Assembly robot movement:** The robot moves along the structure and introduces disturbances.
- **Antenna SYSID:** The MCI and flexible properties of the antenna are estimated.

For **Orbital Simulator** the campaigns were:

- **Transfer to capture stack:** The tug performs impulsive manoeuvres to approach a stack launched at a lower orbit drifting away from the initial position.
- **Navigation sensitivity:** An analysis changing the navigation algorithm performance studied the robustness of the guidance system to uncertainties in the state.

Fig. 8a and Fig. 8b provide a sample of the results and statistical metrics obtained during the test campaign. It shows the dispersion in position at capture as a trajectory in the capture plan and a histogram of dispersion, with the red circle representing the target requirement. All the results fulfilled the requirements and demonstrated that the capture, relocation, and assembly operations can be performed successfully with the proposed algorithms.

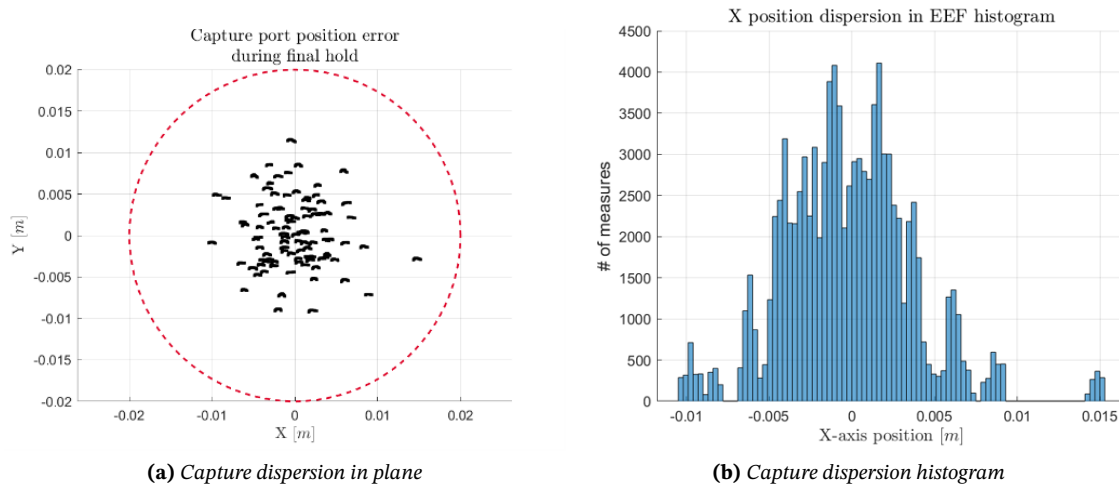


Figure 8 *Statistic plot for Capture scenario with MIL campaigns at the end of Phase 1.*

2.4 Phase 1 Conclusions

Phase 1 established the technical foundations of the IOANT concept through the definition, development, and extensive MIL validation of a complete GNC framework for in-orbit assembly of large antennas. The study demonstrated at simulation level that the proposed architecture can robustly support the full assembly lifecycle, including orbital rendezvous, capture, mating, relocation, and assembly operations under significant uncertainties and evolving system dynamics. The developed model-based coordinated control algorithms successfully handled the strong coupling between spacecraft and manipulators, while the orbital guidance framework proved capable

of autonomously managing large state dispersions and navigation uncertainties. In parallel, system identification techniques showed promising results for estimating flexible dynamics and supporting controller tuning throughout the assembly process. The validation campaign confirmed that the proposed GNC architecture can accommodate large variations in mass, centre of mass, inertia, and structural flexibility while maintaining stability and performance.

Phase 1 provided a clear roadmap for the subsequent technology maturation activities to be carried out in Phase 2. Although the MIL validation campaign demonstrated the feasibility and robustness of the proposed GNC architecture, it also highlighted the need to validate the developed algorithms in increasingly representative environments. The next phase should therefore develop representative proof-of-concept facilities capable of reproducing the most critical aspects of in-orbit assembly operations, including spacecraft-manipulator interaction, capture and mating manoeuvres, and the evolution of system mass and flexibility throughout the assembly process. A second recommendation concerns the progressive maturation of the software development and verification chain from simulation to operational systems required extending validation beyond MIL environments through Hardware-in-the-Loop (HIL), and Dynamics-in-the-Loop (DIL). Additional emphasis must be placed on increasing confidence in the dynamic models and control design assumptions through correlation between simulation and experimental data, while further investigating the interaction between large flexible structures and robotic assembly operations. These recommendations directly shape the objectives of Phase 2 described in the next section, whose primary goal is to experimentally validate the key GNC technologies and advance their maturity from simulation-based verification toward representative environments.

3 Phase 2 – Ground Proof-of-Concept Experimental Validation

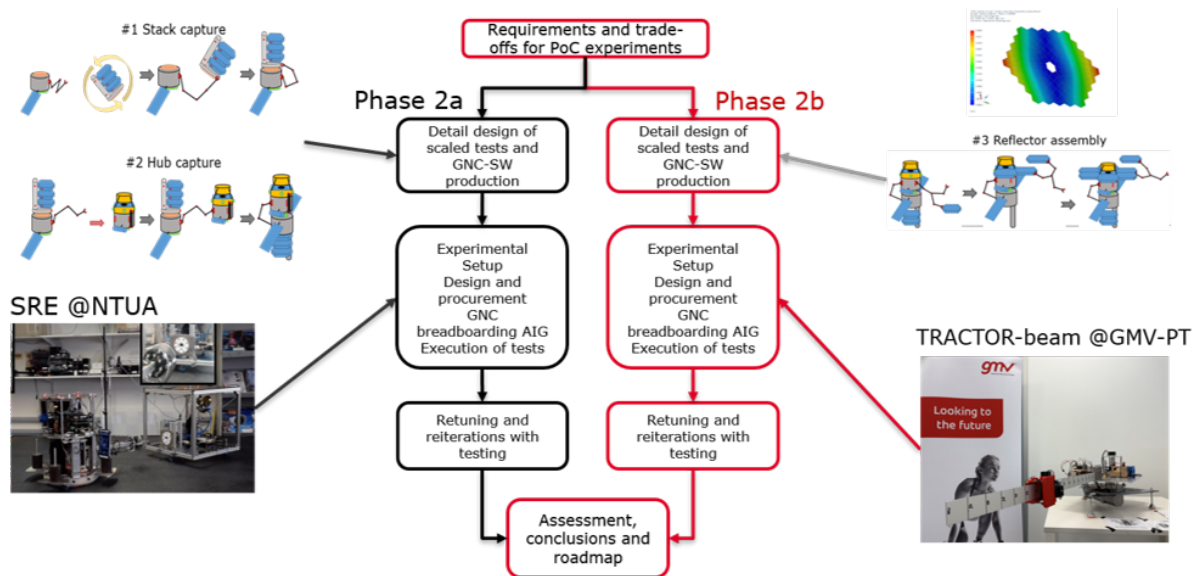


Figure 9 Phase 2 of the IOANT activity, with two lanes using two different facilities for ground experiments covering complementary operations of the IOANT concept.

Phase 2 of the IOANT, Fig. 9, focuses on the experimental validation of the GNC concepts developed during Phase 1 through the implementation of representative ground-based Proof-of-Concept (PoC) testbeds. The work performed in this phase is structured along two complementary axes:

- the development and validation of flight-representative GNC software, and
- the design, implementation, and operation of hardware-based experimental platforms for validation.

The GNC algorithms developed and validated in MIL during Phase 1 were transitioned towards more representative execution environments, through auto-coding of validated onboard GNC functions into C code and Intermediate MIL-SIL verification to ensure consistency and numerical stability. These steps enable progressive maturation of

the GNC software, ensuring robustness against implementation effects such as numerical precision, execution latency, and processor limitations.

The validation campaign focuses on a reduced but representative subset of test cases derived from Phase 1, ensuring coverage of the main GNC functionalities and interfaces while maintaining tractability of real-time testing. For the Phase 2 of the project, there are three points that can be studied in more detail, benefitting from hardware tests performed on ground:

- 1) The system identification techniques benefit from testing them using hardware, considering effects that are not easily modelled in a Simulink environment.
- 2) Although model-based PD improved the tracking performance, unmodelled effects such as joint friction and actuator nonlinearities affect significantly the steady state error. This can be addressed by model-based PID controllers resulting in a more realistic assessment of system performance and robustness.
- 3) Simplified flexible models can be developed to test the hypothesis made about the flexible dynamics with moving elements, and to try control techniques under the presence of larger variations of MCI and flexible properties.

To complement the software validation, Phase 2 includes the development and use of experimental facilities designed to emulate key aspects of in-orbit assembly dynamics and provide HIL testing. These activities are structured around two complementary experimental frameworks, Fig. 9:

- The Space Robotics Emulator (SRE) [13] for robotic assembly operations.
- The Central Module (TRACTOR-beam) [14] for flexible and time-varying dynamics during assembly.

These two facilities allow testing different parts of the project: SRE is focused on manipulator control and non-linear dynamics, while TRACTOR focuses on the assembly control and variation of MCI/flexible properties.

3.1 Space Robotics Emulator

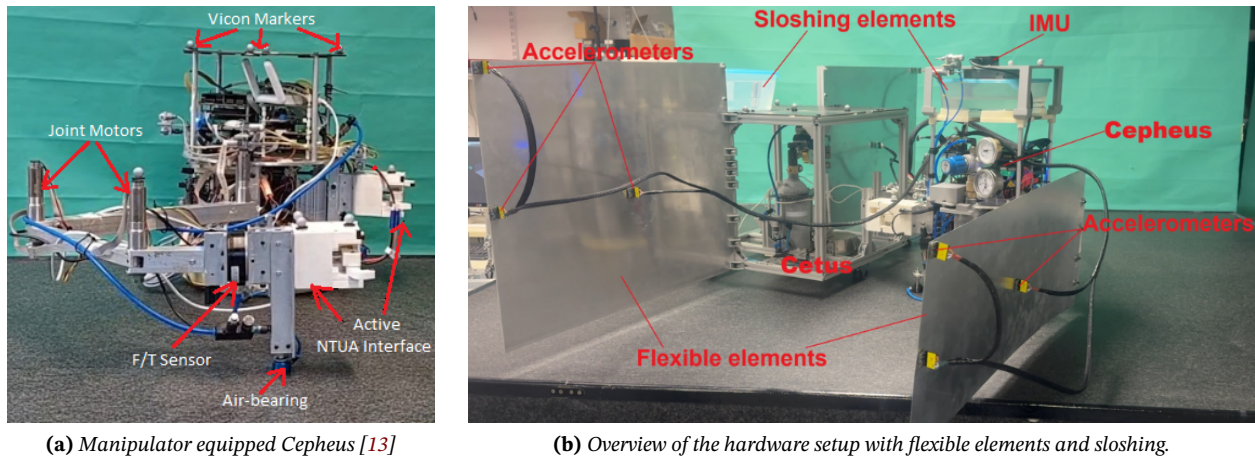


Figure 10 SRE: Overview of the scaled module with flexible and sloshing elements [13]

The SRE's air-bearing zero gravity test facility of the Control Systems Laboratory (CLS) at NTUA was employed to emulate planar micro-gravity conditions during robotic operations and provides a test-bed for the validation of manipulator deployment and coordinated control, capture and mating operations between spacecraft elements, contact dynamics during docking and assembly and system identification of flexible modes and sloshing dynamics. This facility has been already in several ESA projects and includes a planar manipulator-equipped satellite mock-up and other floating passive or active mock-ups. The CSL SRE emulates a zero-gravity planar environment for studying the dynamics and control of on-orbit space systems with or without manipulators, while performing common On-Orbit Servicing (OOS) tasks, such as docking, berthing, assembly, passive object handling, etc. Fig. 10a shows a version of the satellite mock-up equipped with a manipulator and a gripper interface, called Cepheus, while Fig. 10b illustrates an IOANT Phase 2 experiment at its initial phase.

The facility provides high-fidelity representation of contact dynamics and interaction forces under quasi-frictionless conditions, allowing detailed validation of control laws under representative disturbance environments. The SRE consists of a black hard rock table, three floating robotic satellite mock-ups (of adjustable mass and inertia, two active – one passive), workstations and other peripheral devices required for the operation (Vicon MoCap system, overhead camera, Wi-Fi routers, etc.). To eliminate residual vibrations from the environment, the emulator is located at the basement test rig of the NTUA-CSL. The largest part of the emulator is the hard rock table of extremely low roughness (about $5\text{ }\mu\text{m}$ mean value), of 2.2 m length and 1.8 m width (about 4m² of surface in total). Satellite/ robot mock-ups, equipped with CO₂ tanks float on the table using air bearings that lift the robots about $10\text{ }\mu\text{m}$ above the table, providing essentially frictionless motion. Since the robots are fully autonomous, there are no external disturbances from cables or pipes, resulting essentially in zero-g planar motion emulation. Around the hard rock table, several workstations are dedicated for telemetry and control of the floating robotic mock-ups.

SRE Tests Description and Results

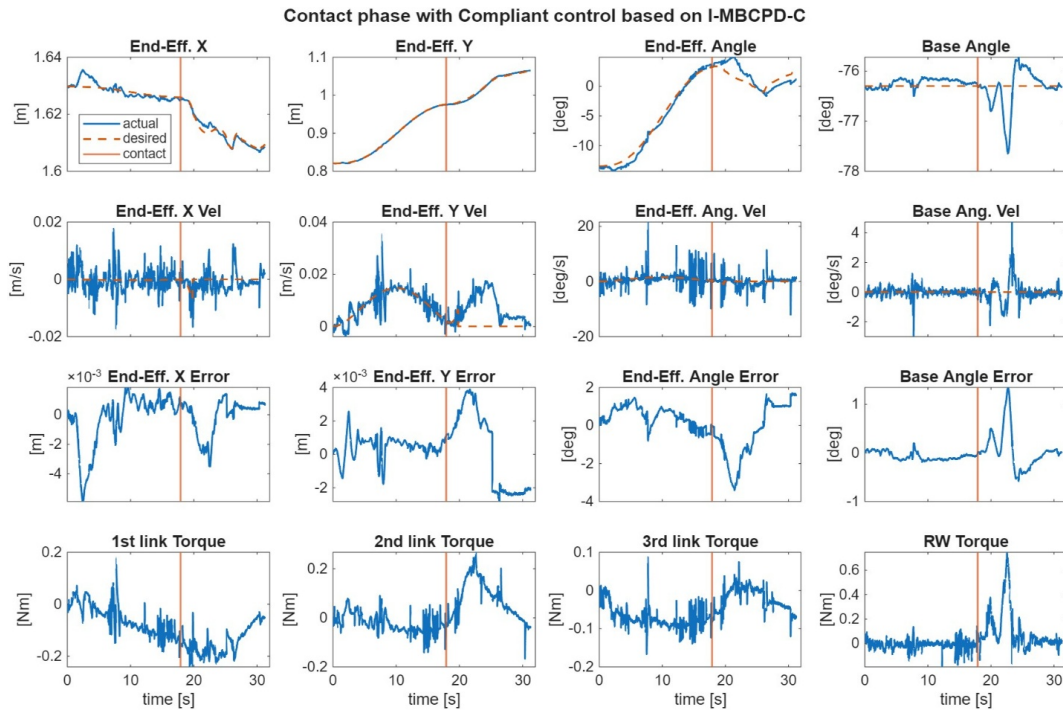


Figure 11 Example results for Model-based PD

At the SRE facilities, the actuated IOANT Tug-Stack mated system, and the passive IOANT Central Module spacecraft (SC) are emulated in scaled-down mock-up versions. The mated Tug-Stack mock-up is Cepheus while the Central Module is emulated by Cetus (passive) [13]. The experimental campaign includes four main categories:

- 1) Manipulator deployment
- 2) Central Module capture
- 3) Manipulator-induced mating
- 4) System identification experiments

These experiments aimed to validate:

- Joint-space and Cartesian-space model-based coordinated controllers
- Robust control augmentation using H_∞ techniques
- Compliant control behaviour during contact and closed kinematic chain formation
- System identification techniques for flexible dynamics and sloshing

The hardware experimental campaign enabled the evaluation of the proposed model-based controllers under realistic operating conditions, where modelling uncertainties and hardware-induced non-linearities are inevitably present. Such effects include joint friction, actuator limitations, sensor noise, variations in mass properties and inertia, as well as unmodelled flexible dynamics. These experiments provided valuable insight into the robustness of the proposed control schemes and their suitability for realistic on-orbit servicing operations.

The experiments validated key capabilities of the system, including manipulator deployment and control, attitude regulation, and the execution of manoeuvres required for system identification. The model-based PD controllers demonstrated trajectory tracking, with minor steady-state deviations attributed to unmodelled dynamics, external disturbances, and suboptimal gain tuning.

During the contact phase, the incorporation of compliant control characteristics proved critical. The compliant behaviour reduced external forces and mitigated structural strain during interaction, thereby preventing excessive contact loads and improving the robustness of the docking process. Overall, the results demonstrate that the proposed control laws can effectively adapt to the varying requirements of each phase of the mission, Fig. 11. During the system identification experiments on the scaled-down SRE facility, translational motion was achieved with minimal rotational disturbance, confirming the effectiveness of the thrusters and RW configuration, for experiments supporting the identification of system parameters of the Tug-Stack, Fig. 12.

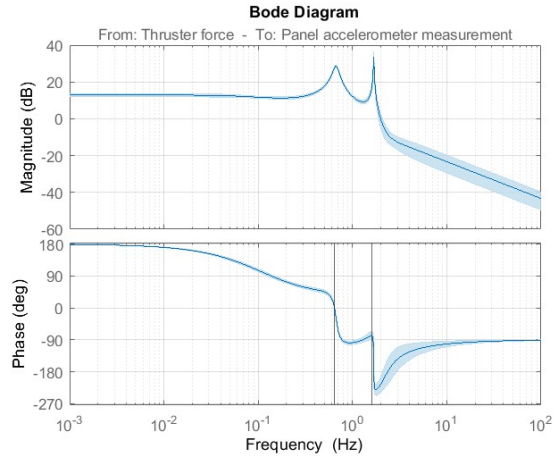


Figure 12 Confidence intervals for the system natural frequencies through identification with measurements from the accelerometer on the flexible element tip.

3.2 TRACTOR

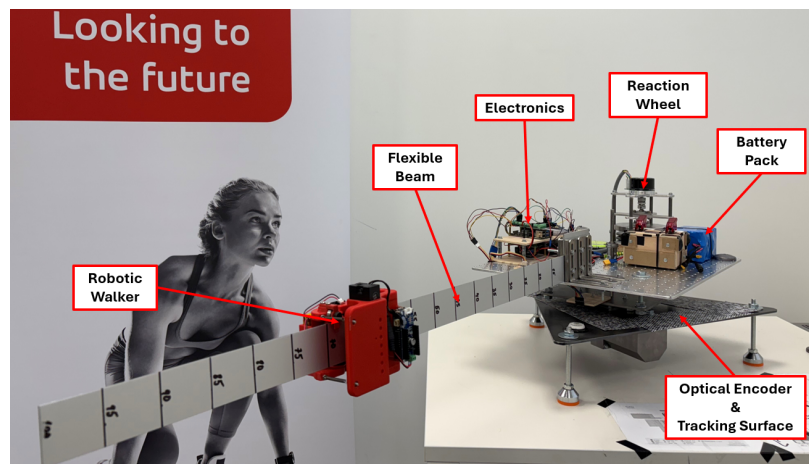


Figure 13 Overview of the TRACTOR testbench for the validation of the assembly controller.

The bespoke scaled test-bench in Fig. 13 was developed to emulate the attitude dynamics of the central module during the assembly process, tailored to have:

- Variations in mass, centre of mass, and inertia properties
- Variations of the flexible structural dynamics (to mimic the challenges in large antenna elements)
- Disturbances induced by assembly operations

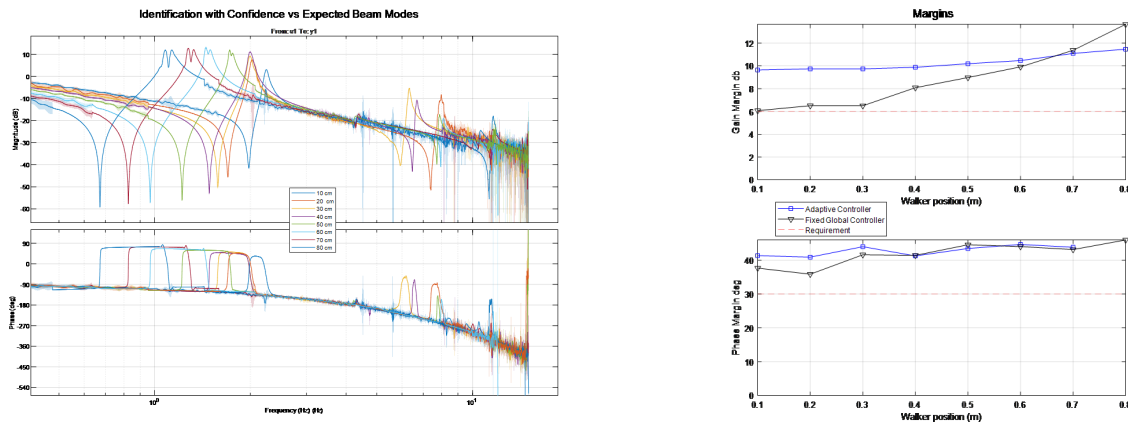
The TRACTOR test-bench [14] depicted in Fig. 13 was set up to cover experimentally the main challenges of IOA, primarily the variation of properties and low friction. The structure of the TRACTOR was designed as a test-bed that is lightweight, low-friction, modular, and easy to calibrate to evaluate GNC solutions, composed of a static assembly and a rotating assembly.

A static base supports the rotating assembly, providing a flat reference surface for calibration and serving as the tracking surface for the optical encoder. The triangular steel base sits on three adjustable feet, forming a determinate (three-point) support that allows levelling perpendicular to the local gravity vector. It also houses a thrust ball bearing for axial support and a shaft to bear lateral displacements. The upper platform is a gridded plate that provides a modular mounting pattern for components. The rotating assembly carries the actuators, electronics, batteries, sensors for wireless Hardware-in-the-loop tests. A flexible metal beam is appended to the base, with a robotic **Walker** mounted on the beam, and able to grip and move along the beam, following velocity profiles sent by the computer on the rotating base.

Several design decisions addressed the variation of flexible and MCI properties, as well as the representativeness of the space dynamics and hardware. The characteristics of the beam, along with the walker mass and position on the appendage, determine the natural frequencies of the flexible system. To maximize the testing envelope of frequencies, it is necessary a range of frequencies and achievable MCI properties suitable for the IOANT experiments. The choice of an aluminium beam resulted from a fine trade-off considering that:

- Longer, more flexible beams offer a broader range of motion for the sliding mass and larger variations in frequency and inertia. However, these are more prone to structural instabilities (torsion), and the centre-of-mass offset can increase the strain on the platform rotation system and the friction.
- Beams with higher flexibility yield lower resonant frequencies but for very low frequencies, the duration of the experiments has to be extended to observe multiple oscillations of the beam. Also, damaging static structural instabilities can appear.
- Stiffer beams yield higher resonant frequencies, which may not be actively controlled due to too high authority, lack of actuation bandwidth, or lack of observability.

With regards to space representativeness, there are a series of effects that need to be accounted for. The friction needs to be minimized to reduce the strain on the control system and not affect the flexible dynamics. This is achieved by minimizing the number of contact points on their surfaces to reduce friction. The setup is also completely wireless to reduce hanging elements with the data transfer performed via wi-fi, and system electronics powered by a battery.



(a) TRACTOR experiment frequency responses for different positions of the Walker along the beam: between 10cm and 80cm from the central platform.

(b) Phase and gain margins for the fixed-gain vs the margins achieved with the adaptive scheduling.

Figure 14 Open loop identified plants, and resulting margins obtained by the fixed-gain and adaptive control designs.

Tests Description and Results

The test campaigns in TRACTOR aimed at validating the design, manufacturing and integration process of the platform by means of several system identification experiments, then a series of control strategies were implemented and compared. The platform properties were estimated for multiple positions of the walker exciting the plant with a torque broadband noise signal. The frequency response of the system was estimated via spectral analysis, using the MATLAB `spa()` function [15], with the frequency responses for the different walker positions shown in 14a, alongside the 99.7% confidence interval. The experiment provides an wide variation of inertia and resonances to challenge the central module GNC approach.

The main result is that having scheduled gains adapting to the configuration of the platform, we can recover stability margin and some performance w.r.t. invariant gains, demonstrating the benefit of updating the controllers to account for the MCI properties of the built setup. Fig. 14b shows the gain and phase margins for a fixed-gain system and a scheduled system: the scheduling provides similar margins throughout the envelope of platform properties, while the fixed-gain control is limited by the closest position at 10cm. This translates into the results seen in 15a and , where for fixed-gains, where for variations of the walker in the full position envelope degrades the relative performance, with respect to the adaptive scheme developed during IOANT Phase 1.

The tracking capabilities of the setup have been demonstrated for different configurations of the platform (walker positions), and the GNC implementation in TRACTOR was validated in the frequency domain by comparing the closed loop design using the identified plants of Fig. 14a versus a system identification of the closed loop system, Fig. 16.

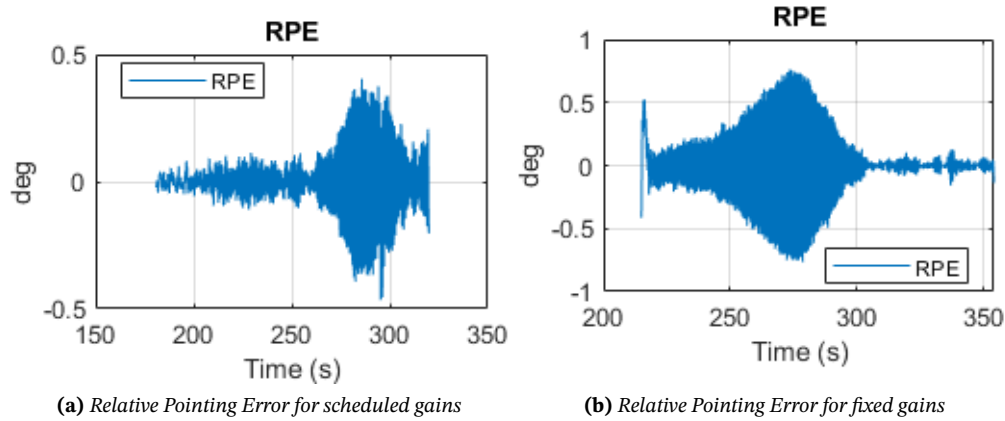


Figure 15 Relative Pointing Error of the adaptive schedule control, versus the fixed-gain control.

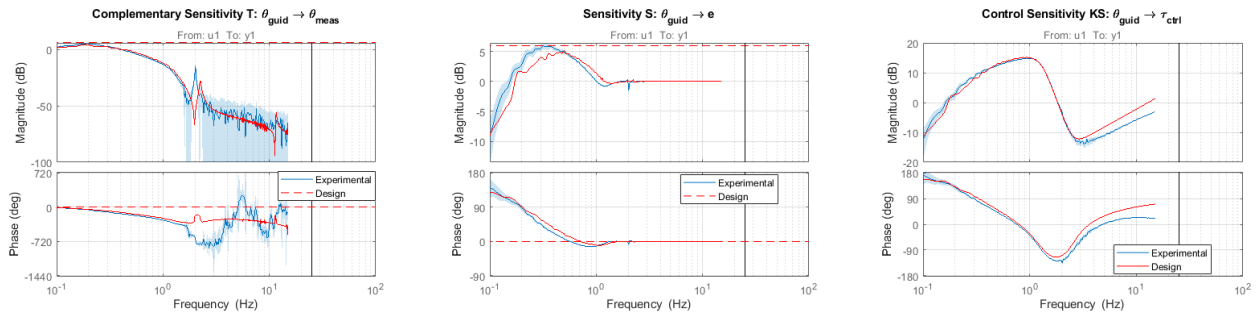


Figure 16 Closed loop SYSID vs open loop SYSID closed in tuning

3.3 Phase 2 Conclusions

Phase 2 took the concepts from simulation-based validation to representative experimental environments, significantly increasing the maturity of the proposed GNC technologies. Through the SRE and the TRACTOR-beam proof-of-concept platforms, the project experimentally validated coordinated spacecraft-manipulator control, autonomous capture and mating operations, system identification techniques, and control strategies for systems with evolving flexible dynamics. The results demonstrated that model-based coordinated controllers can achieve accurate tracking and stable operation under realistic disturbances, while compliant control effectively reduces contact forces during physical interaction.

System identification experiments confirmed the feasibility of identifying structural and sloshing dynamics in operationally relevant conditions, supporting adaptive control and model updating. Furthermore, the TRACTOR-beam campaign showed that gain-scheduled control significantly improves stability and performance for systems subject to time-varying inertia and flexibility, validating one of the key assumptions of the IOANT architecture. Overall, Phase 2 provided the first representative hardware validation of the proposed in-orbit assembly GNC framework and advanced the technology readiness of the main building blocks from simulation-based concepts toward TRL 5.

4 General Conclusions and Future Work

The IOANT project successfully demonstrated the strong potential of GNC to support IOA as an enabling technology for next-generation large-scale antennas and modular space infrastructures. Structured in two complementary phases, the project first established a complete GNC and autonomy framework through extensive modelling, simulation, and verification activities, and subsequently validated the most critical technologies through representative hardware-based proof-of-concept demonstrations. Overall, Phase 1 established a credible technical foundation for future scalable in-orbit assembly missions and highlighted the significant opportunities offered by autonomous on-orbit construction for large antennas and other modular space systems. Through this progressive maturation approach, advanced GNC, robotic manipulation, and system identification techniques were successfully developed and validated for autonomous assembly operations involving evolving mass, inertia, and flexible dynamics. The study also highlighted key limitations. The most significant challenge is the strong dependence of system behaviour on time-varying mass, inertia, centre-of-mass location, and flexible structural properties, which the activity shown directly affecting control performance and observability. Contact dynamics during capture, mating, and rigidisation operations remain critical drivers for system design, requiring compliant interaction strategies and robust control architectures.

The Phase 2 experiments increased confidence in the concepts, and provided important lessons. First, variations in inertia and flexibility must be treated as primary design drivers rather than secondary effects, making adaptive or gain-scheduled control strategies essential. Second, coordinated control of manipulators and spacecraft platforms is required to achieve stable and efficient operations. Third, system identification is a key operational capability for updating dynamic models and avoiding structural mode excitation, even its effectiveness strongly depends on excitation conditions and sensor placement.

Finally, the project's two-phase approach was valuable for progressive validation, from simulation to hardware testing, and that proof-of-concept platforms can effectively mature critical technologies with controlled development cost and complexity. However, the validation remained short of flight representativeness, since effects like long-duration microgravity operations, thermal environments, and full-scale structural coupling were not reproduced. Future work should focus on maturing the technology from successful proof-of-concept demonstrations toward a flight-oriented in-orbit assembly system.

Key priorities for future work include further expansion of robust adaptive and gain-scheduled GNC algorithms to handle large dynamic, improve compliant control for capture and mating, increase realism of navigation and sensor-fusion, and lift the software toward flight real-time implementation. Further standardization of assembly interfaces is also recommended with a progressive validation roadmap, extending from MIL/SIL/PIL environments to larger-scale hardware demonstrations, followed by in-orbit demonstration. The proposed architecture and concept remains based on a modular tug-assisted assembly concept with autonomous manipulation, onboard system identification, and advanced mode management, while future validation should place greater emphasis on scalability, operational realism, and off-nominal and contingency scenarios, to support the transition from TRL 5 to flight-ready systems.

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