EROSS PROJECT – COORDINATED CONTROL ARCHITECTURE OF A SPACE ROBOT FOR CAPTURE AND SERVICING OPERATIONS

V. Dubanchet (1), P. Lopez Negro(1), D. Casu (1), A. Giovannini (1), G. Rekleitis (2), K. Nanos (2), I. S. Paraskevas (2), E. Papadopoulos (2)

(1) Thales Alenia Space – 5 allée des Gabians, 06150 Cannes (FRANCE),
{vincent.dubanchet, davide.casu, anne.giovannini}@thalesaleniaspace.com
(2) National Technical University of Athens, 9 Iroon Polytechniou str., 15780 Zografou (GREECE)
{georek, egpapado}@central.ntua.gr, {knanos, isparas}@mail.ntua.gr

ABSTRACT

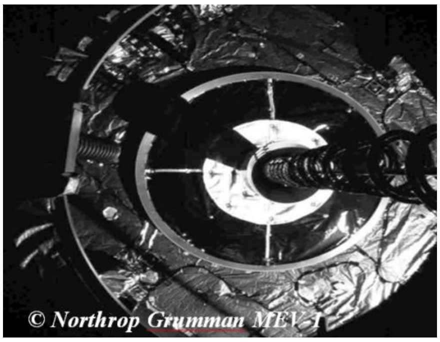
The current developments of On-Orbit Servicing operations are massively investigating the usage of space robotics to realise precise tasks in an autonomous way. Such technologies for usage in space raise the issue of coordinating the motion of a robotic arm mounted on a floating platform, often referred to as "space robot", to ensure proper tracking and/ or capture of a target object floating as well. With that respect, this paper introduces an overall Guidance, Navigation and Control (GNC) scheme along with the vehicles design in the scope of a collaborative rendezvous and space servicing. The functional link between the platform & robotic controllers are presented to answer the different mission needs. The theoretical foundations of the coordinated control are then recalled for each mission phase requiring the absolute and relative motion to perform, respectively, the capture and exchange of a replacement unit. Simulation results are eventually presented and discussed to show the reachable performances of this GNC architecture.

1 INTRODUCTION

The space robotic developments have been going through a real breakthrough over the last five to ten years with the impulse and rising of new markets such as the On-Orbit Servicing (OOS) or the autonomous In-Orbit Assembly (IOA) of space structures. This first mission of application became a reality on February 26th, 2020 with the premiere of an on-orbit service by a Servicer spacecraft to a Client one when Northrop Grumman successfully docked their Mission Extension Vehicle-1 (MEV-1) vehicle to the Intelsat 901 (IS-901) spacecraft to extend its life duration at a geostationary slot[1].

Over the last 20 years, space robotic systems have known important steps forward toward on-orbit servicing with missions like the Japanese *Engineering Test Satellite VII (ETS-VII)* in 1997 [1], the American *Orbital Express* in 2006 [2], and lastly with the first servicing mission mentioned above with the MEV-1 demonstrated by Northrop Grumman, see Fig. 1. In all cases, the systems complexity is constantly increasing to tackle more advanced tasks in the most autonomous way. Robots indeed allow to shift the performance of high-risk tasks from astronauts to mechanical systems, and thus reduce human exposure and impact of life support systems at system level.

[1] [last access: 12/05/2021] https://news.northropgrumman.com/news/releases/northrop-grumman-successfully-completes-historic-first-docking-of-mission-extension-vehicle-with-intelsat-901-satellite



(a) (b)

Figure 1: (a) Autonomous rendezvous and docking by Orbital Express (credit: DARPA), and (b) First on-orbit servicing by MEV-1 mission (credit: Northrop Grumman

With that respect, the European Commission is leading the Strategic Research Cluster (SRC) in Space Robotics to boost the maturity and the synergy of the industrial and academic European actors in this domain. Since 2016, three main suites of projects, also called "Operational Grant" (OG), have been led with a first set from OG1 to OG6 in 2016-2019 to develop robotic building blocks [3-7], and a second set from OG7 to OG11 in 2019 to 2021 to integrate them towards orbital/planetary missions [8-10]. The last step is now engaged to mature the mission of demonstration described in [11][2] with the last OG12, OG13 and OG14 [12]. This plan is summarized in Fig. 2 with the names and scope of the different OGs.

Within this SRC in Space Robotics, Thales Alenia Space has been leading the OG4-I3DS on smart sensors development, OG7-EROSS on integration and validation of the past robotic building blocks towards a servicing mission, and now OG12-EROSS+ to lead the phase A/B1 towards the mission of demonstration of the orbital servicing mission.

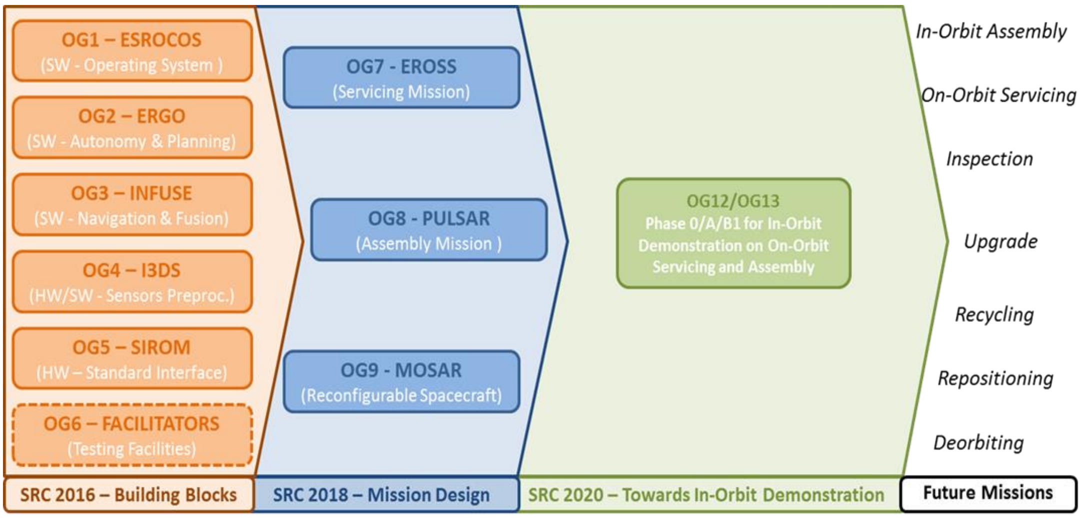


Figure 2: Workflow of past and present Operational Grants within the SRC in Space Robotics.

In the scope of the "OG7 - European Robotic Orbital Support Services" (EROSS) project, Thales Alenia Space benefits from the support of all his core partners GMV, SINTEF AS, National Technical University of Athens (NTUA), PIAP Space, SENER, SODERN, Space Application Services, along with the additional collaboration of the Canadian champion MDA to design the robotic arm, and with QinetiQ to design an alternative docking solution.

[2] [last access: 12/05/2021] https://ec.europa.eu/research/participants/data/ref/h2020/other/guides_for_applicants/h2020-supp-info-space-27-18-20_en.pdf

The paper is organised as follows: a first section recalls the EROSS servicing mission with a glimpse of the vehicle design and architecture for both the Servicer space robot and the Client spacecraft used to demonstrate this servicing operation. A second section focuses on the overall Guidance, Navigation and Control (GNC) architecture with the platform and robot coordination, where the theoretical foundations of the coordinated control are introduced. A third section provides some simulation results of the reachable performances for the different mission steps with the berthing and mating with the Client.

The EROSS project is co-funded by European Union's Horizon 2020 research and innovation program under grant agreement N°821904 and part of the Strategic Research Cluster on Space Robotics Technologies as Operational Grant n°7 [13].

2 MISSION CONCEPT

The EROSS mission scenario focuses on the last steps of a traditional rendezvous in space between a Servicer spacecraft chasing a Client spacecraft to be serviced. After the orbit injection by the launcher, a first set of orbital manoeuvres puts the Servicer within the orbital plane of the Client, then a second set of manoeuvres brings it closer to the Client, either behind or above it [14]. The final forced motion allows the Servicer to perform a straight line relatively to the Client to capture it by its robotic arm; this is the so-called "berthing" phase as opposed to a direct "docking" phase [14]. The **coordinated control** of the Servicer space robot is then designed to allow a smooth and safe motion of the platform and of the robotic arm in a synchronous way [15-18]. The coordinated control is used during the deployment of the robotic arm, while the Servicer platform is pointing towards the Client to maintain this latter within the rendezvous sensors Fields-of-View (FoV), during the capture phase, to track the grasping feature while maintaining a safe relative attitude of both platforms, and eventually to mate the two vehicles through refuelling interface and to exchange the ORU unit from one platform to the other.

2.1 Mission Description

The focus of the EROSS project is on the last forced motion, the berthing, and servicing operations, while the initial orbital manoeuvers to phase it within the Client orbital plane and to synchronize its true anomaly are considered already performed [14], see Fig. 3.

The scenario for EROSS validation can be split into two main phases to cover the final rendezvous and capture with a high autonomy:

- **Phase E - Mating**: final approach, station keeping, coordinated/compliant robotic capture;
- **Phase F - Servicing**: berthing, refuelling, robotic exchange of a replaceable unit.

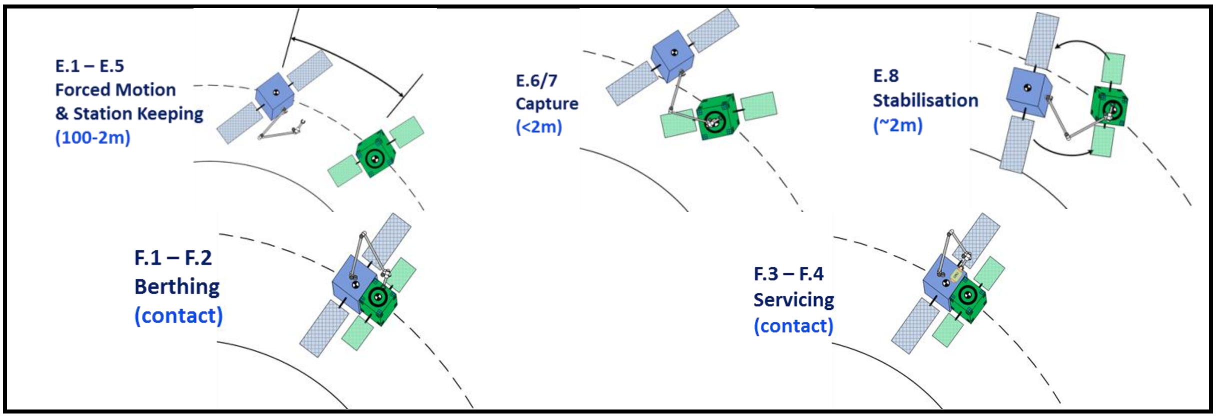


Figure 3: EROSS Mission Description with (E) approach & capture, (F) berthing & servicing.

The EROSS Servicer space robot must then fulfil the following functions, whose details are summarized in the scheme below with respect to the Client local orbital frame, see Fig. 4:

- **Final Approach**: The Servicer is already tracking the Client within its sensors FoV. It performs a continuous forced motion to approach the Client along a straight line;
- **Berthing**: This is the first step of the coordinated control with the Servicer platform maintaining a relative berthing position and attitude with respect to the Client while the robotic arm is deployed and move towards the grasping feature to capture it;
- **Servicing**: Once the two platforms are rigidly linked through the robotic link, the Servicer mates with the Client by reconfiguring its robotic arm and plugging the refuelling interface. Two types of servicing are then demonstrated with the refuelling through the ASSIST interface and the exchange of an Orbital Replacement Unit (ORU) equipped with two SIROM standard interfaces to dock on the hosting platforms;
- **Release**: Following the same steps in the opposite order, the two spacecrafts are eventually released after a grasping, interface release, and eventually separated by the robotic arm before the natural laws of orbital dynamics and a single boost manoeuver take the Servicer away from the Client in a safe way.

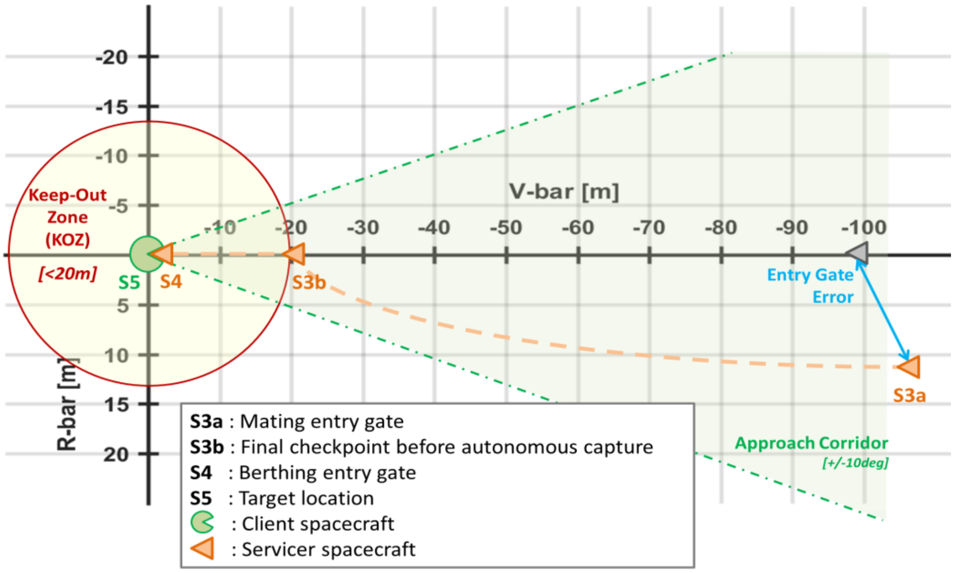


Figure 4: EROSS final forced motion to approach and capture the Client vehicle.

2.2 Servicer Vehicle Design

The Servicer system design has been elaborated by Thales Alenia Space in France through several studies with the CNES and ESA space agencies, as well as with internal funds to be optimized for future servicing missions.

Its hexagonal platform of less than 5 m of diameter and 2 m height, see Fig. 5, allows it to reach a compact form factor. This shape stems to the compact volume constraints to ease the attitude control and clearance for rendezvous and capture, but also to maximize the upper panel for the robotic bay. This upper side is dedicated to the robotic equipments dedicated to the rendezvous: the refuelling interface on top of a mast, the relative rendezvous sensors, and the robotic arm with its own set of sensors at the end-effector.

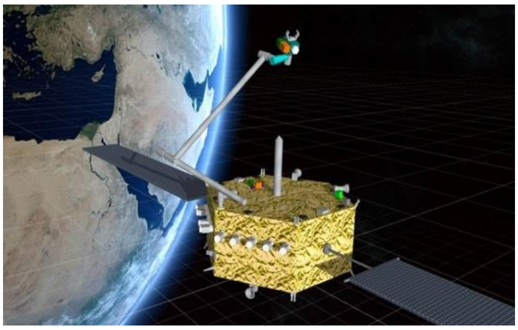


Figure 5: EROSS Servicer design.

The lateral parts are composed of 6 panels. On two of them, the rollable solar arrays are accommodated diagonally opposed and developed by Thales Alenia Space in France for years. This innovative solution is required as the electrical propulsion choice implies high power for orbital transfer phases as well as during the servicing phase to feed the Client with electrical power. On the contrary, the Servicer requires much less power during the rendezvous and capture phase, when the solar panels are rolled in stowed position to maximize the clearance and minimize the risk of collision during the robotic motion.

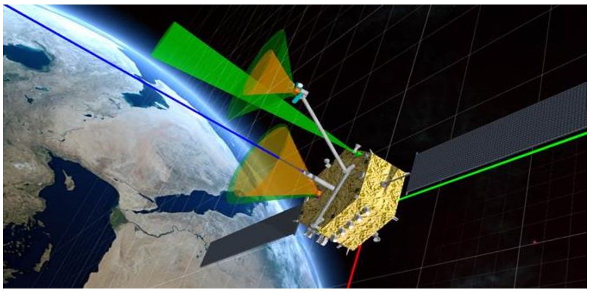


Figure 6: Rendezvous and robotic sensors FoV with the deployed arm.

Two of the lateral panels are dedicated for the ORU units accommodation. For this purpose, it accommodates 10x SIROM interfaces on the Servicer platform, with a payload capacity of 9x ORUs loaded on the previous interfaces. Each of them is assumed to be exchanged with a serviced Client to either repair or upgrade it during the whole Servicer mission. One slot is left free to handle the unit transfer during the Client servicing.

The Servicer On-Board Software (OBSW) and GNC design inherit from the past H2020 projects mentioned above with the past Operational Grants (OG). It reuses and integrates:

- the ESROCOS software layer from OG1 [3] and the ERGO autonomy framework of OG2 [4] both developed by GMV,
- the INFUSE data processing of OG3 [5] developed by Space Applications Services,
- the I3DS sensors integrated through an ICU processing board within OG4 [6] developed by Thales Alenia Space with the complete software (SW) integration by SINTEF,
- the SIROM standard interface from OG5 [7] developed by SENER,
- and the validation facilities from OG6 handled by GMV for the orbital tests.

In parallel, the EROSS project also integrates customized elements such as the robotic arm designed by MDA, the ARAMIS rendezvous sensor developed by SODERN, the ASSIST docking and refuelling interface by GMV, and a capture gripper developed by PIAP-Space.

2.3 Client Vehicle Design

The Client spacecraft considered within the EROSS project is derived from the Sentinel-3A spacecraft developed by Thales Alenia Space. This client satellite is supposed to be **prepared and cooperative** to be serviced, meaning that slight customization is performed to enable the rendezvous, capture and servicing tasks:

- An ASSIST passive interface is added outside the Launch Adapter Ring,
- A SIROM interface is added on the payload panel for the Orbital Replaceable Unit (ORU) exchange,
- Passive rendezvous aids are added at different locations.

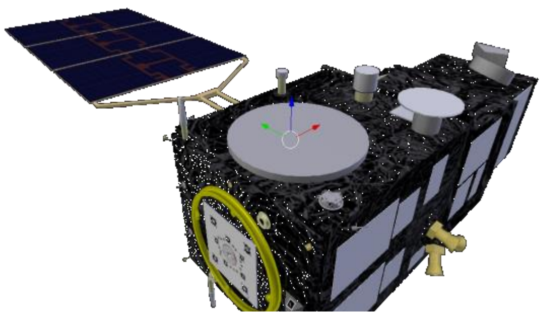


Figure 7: Client satellite based on the Sentinel 3 design

3 EROSS CONTROL ARCHITECTURE

From the GNC point of view, the Servicer vehicle is seen as a traditional platform when its robotic arm is stowed. During that time, the platform controller is based on traditional techniques developed within Thales Alenia Space to ensure the proper thruster pointing during the orbital manoeuvres, to maintain the solar panels illumination for power generation, while also keeping track of the Client spacecraft within the relative sensors FoV when the relative navigation starts. On the other hand, as soon as the robotic arm is deployed during the capture and servicing steps, the Servicer switches to its "space robot" operational modes [2-3-4] with the coordination of its multiple Degrees-of-Freedom (DoF) to move and align the arm end-effector around the Client spacecraft while maintaining its platform inertial pointing.

Many techniques were developed in the past to control such a space robot free-floating in space. The National Technical University of Athens (NTUA) played a key role in these developments, and is in charge of the robotic coordinated control in EROSS project. Different GNC techniques are summarized in [5] for a space robot, with the main hypothesis of controlling or not the platform when the arm is moving. In the first case, the space robot is said to be "free flying" when the Servicer platform is actuated by the thrusters or reaction wheels to maintain a given pointing while compensating for the disturbances coming from the robotic arm motion. From a practical point of view, this method induces vibrations and a complex controller coupling between the platform and the robotic arm. On the other hand, the platform controller can also be completely switched off to prevent the transmission of any residual vibration from the platform to the arm: the space robot is then said to be "free-floating". This method also presents the additional advantage of saving fuel and power on the platform side, but at the expense of a reduced workspace for the end-effector of the robotic arm, and of the loss of direct position and attitude control of the Servicer base, which may rise safety issues at such proximity [18]. The trade-off performed within EROSS project led to **the selection of the "free-flying" architecture to actively control the platform and the robotic arm through a coordinated compliant controller** to capture the Client with a maximum motion accuracy and robustness [19] [20].

The following sections detail the GNC architecture of both the platform and the robotic arm developed in a complete synergy to ensure the coherence between their operational mode.

3.1 Platform & Robotic Control Modes

The system modes are used to manage either separately or in a coordinate way the Platform and the Robotic arm, depending on the rendezvous phase. They are managed by the Mission and Vehicle Management (MVM) function implemented by the ERGO agent.

The harmonization of the GNC modes between the Platform and the Robotic Arm is made to maximize the system accuracy and safety during the critical phases of the robotic capture for the rendezvous: it is worth recalling that the avionics architecture and the available processing & interfaces capabilities drive the level of coupling between both elements (i.e., data rate, bandwidth, etc.). The robotic arm is considered as **an independent element or payload** mounted on the platform, whose GNC modes are developed in synergy. This means that the robotic arm has its own GNC modes and sub-modes, and its own autonomy, defined in synchronisation with the platform modes, with the platform acting as a "slave" element applying the required forces/ torques and implementing the coordinated control theory.

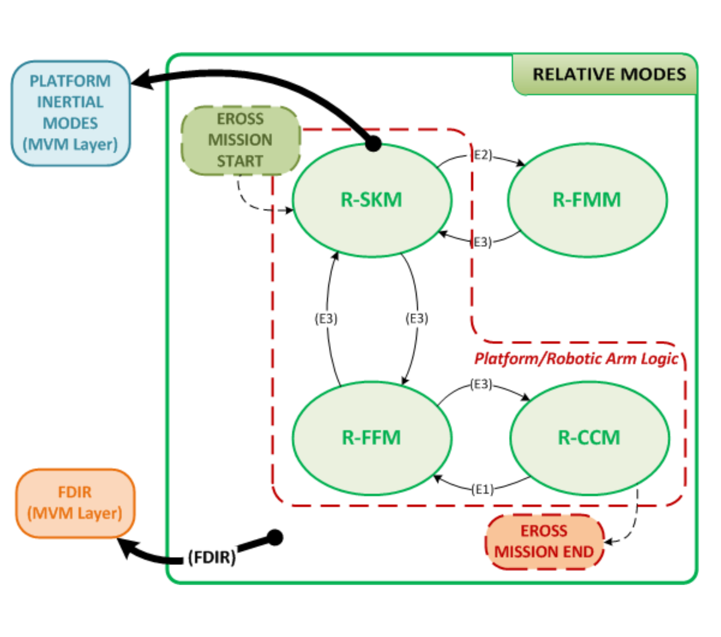
From the GNC architecture point of view, the platform and robotic modes are simultaneously and synchronously triggered by the ERGO agent implementing the autonomous behaviour of the Servicer. This architecture ensures that the coordinated control is handled by the switching of the platform and robotic actuators and sensors within a coherent mode on both sides, as both systems are managed by separate modes.

3.2 Platform Control Modes

Table 1 lists all the control modes defined at the Platform level according to the system modes defined at higher level and meeting a specific need at mission level (e.g., pointing accuracy, safety mode, or coordinated motion).

Table 1: Summary of Servicer platform modes and control sub-modes.

PLATFORM modes *(relative modes only)*	
R-NOM	Relative Nominal Mode
R-HMM	Hoping Manoeuver Mode
R-SKM	Station Keeping Mode
R-FMM	Forced Motion Mode
R-FFM	Free Floating Mode
R-CCM	Composite Control Mode
E-CAM	Collision Avoidance Mode
E-FDM	Free Drifting Mode
CONTROL sub-modes	
FAAC	Fine Absolute Attitude Control
FFMC	Free-Flying Motion Control
CAMC	Coordinated Attitude Motion Control (CAMC)



Fine Absolute Attitude Control (FAAC)

This mode controls the Servicer platform attitude using the set of Reaction Wheels (RW), while the thrusters are inactive. This mode is a traditional platform mode, and acts without coordination with the robotic arm. It aims at ensuring a fine pointing of the platform with low amplitude manoeuvers coming from the guidance. This mode is used when no translational motion from the platform but a fine attitude control are required.

Free-Flying Motion Control (FFMC)

This mode controls the Servicer platform position and attitude (i.e., pose). This 6 DoF control aims at tracking a pre-planned trajectory provided by the platform guidance, either dynamic during forced motion, or static during station keeping. This mode relies on both the thrusters and the RWs to control both the relative position and attitude with respect to the Client.

Coordinated Attitude Motion Control (CAMC)

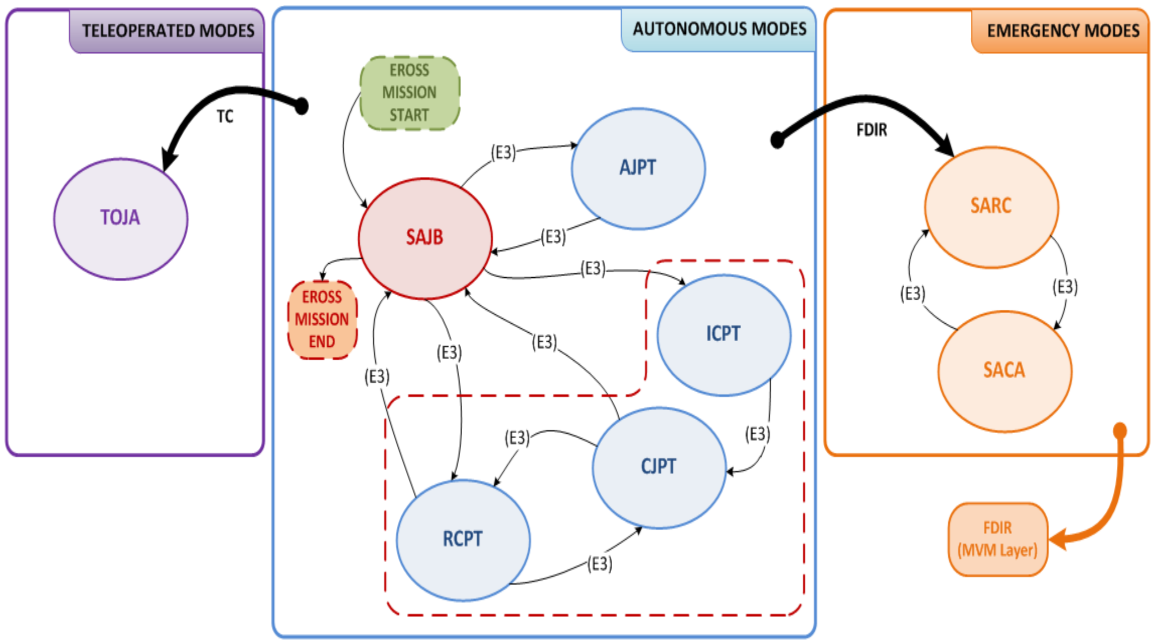
This mode is dedicated to the Client capture and robotic operation to control the attitude of the Servicer platform while the robotic arm is moving. During this mode the RWs are active but receive their commands from the robotic arm controller whose guidance is derived to ensure both the end-effector and the platform control at the same time: this is the so-called “coordinated control” mode. The platform controller is in a “slave” mode receiving the reference torques to be applied from the robotic controller, while the thrusters are OFF.

3.3 Robotic Control Modes

Similarly, the robotic modes are defined to meet mission needs at the "robotic payload" level to deploy the robotic arm, capture the grasping feature on the Client, retrieve it for berthing, or exchange the ORU. For each system mode including a robotic motion, a corresponding robotic mode is defined to be compatible with the platform sensors/ actuators usage. Hereunder, the robotic system modes and the corresponding control modes are introduced in Table 2, and the details of the control mode feedback are given in Table 3.

Table 2: Summary of Servicer robotic modes and control sub-modes.

ROBOTIC modes		CONTROL sub-modes	
SAJB	Safe Arm Joint Braking	TOJC	Tele-Operation Joint Control
TOJA	Tele-Operated Joint Angle motion	AJSC	Autonomous Joint-Space Control
AJPT	Autonomous Joint Planning and Tracking	CJSC	Coordinated Joint-Space Control
CJPT	Coordinated Joint Planning and Tracking	ICCC	Inertial Cartesian-space Compliant Control
ICPT	Inertial Cartesian Planning and Tracking	RCCC	Relative Cartesian-space Compliant Control
RCPT	Relative Cartesian Planning and Tracking		
SACA	Safe Arm Collision Avoidance		
SARC	Safe Arm Retraction at Checkpoints		



A key feature of the robotic modes is the dual coordinated and compliance behaviour of the robotic controller, allowing to simultaneously track the platform and robotic arm reference guidance profiles, while the forces/torques measured at the end-effector are fed back to ensure smooth contact. These double characteristics is key to ensure that the Servicer robotic gripper is not pushing away the Client to capture it, and that the mechanical effort at the gripper level are not increasing exponentially when closing the mechanical loop to berth the two vehicles through the refuelling interface, or to exchange the ORU on both platforms.

Table 3: Details of the robotic control sub-modes.

Acronym	Description	Measurement Feedback	Platform/Arm Coordination	Compliance motion
AJSC	Autonomous Joint-Space Control	Joint states	☒	☒
CJSC	Coordinated Joint-Space Control	Joint states Platform states	☑	☒
ICCC	Inertial Cartesian-Compliant Control	Joint states Platform states Force feedback Visual processing	☑	☑
RCCC	Relative Cartesian Compliant Control	Joint states Platform states Force feedback Visual processing	☑	☑

AJSC : Autonomous Joint-Space Control

A joint-space control is implemented in this mode, so that each joint follows a desired trajectory, provided by the robotic guidance. It can be a Model-Based PD control or even a simple PD control depending on the accuracy constraints in this mode. This is a Non-Coordinated control, used for the robotic arm initial deployment, independent of the separate control law that is controlling the Servicer base station-keeping.

CJSC : Coordinated Joint-Space Control

This mode refers to a Coordinated Model-Based control law, with a joint-space Model-Based PD arm control part, so that each joint follows a desired trajectory, and a Model-Based PD attitude control part for the Servicer platform, so that the platform attitude follows a desired trajectory. Both joint and platform attitude desired trajectories are provided by the respective guidance while the control output is the joint and reaction wheel control torques.

ICCC : Inertial Cartesian-space Compliant Control

This inertial mode implements a Coordinated Model-Based control law, with a Cartesian-space Model-Based end-effector Compliant control, so that the arm end-effector tracks a desired trajectory with respect to the inertial frame having also compliant characteristics, and a Model-Based PD attitude control part for the Servicer platform as mentioned in CJSC. The controller is developed as an inertial reference trajectory tracking control (for both the end-effector pose and the Servicer platform attitude), thus requiring measurements from navigation and desired trajectories generation from guidance with respect to the Inertial Frame.

RCCC : Relative Cartesian-space Compliant Control

This last mode implements another Coordinated Model-Based control law, with a Cartesian-space Model-Based end-effector Compliant control, so that the arm end-effector tracks a desired trajectory with respect to the Servicer base frame, having also compliant characteristics, and a Model-Based PD attitude control part for the Servicer platform, so that the platform absolute attitude still follows a desired trajectory in the inertial frame.

4 COORDINATED CONTROL VALIDATION

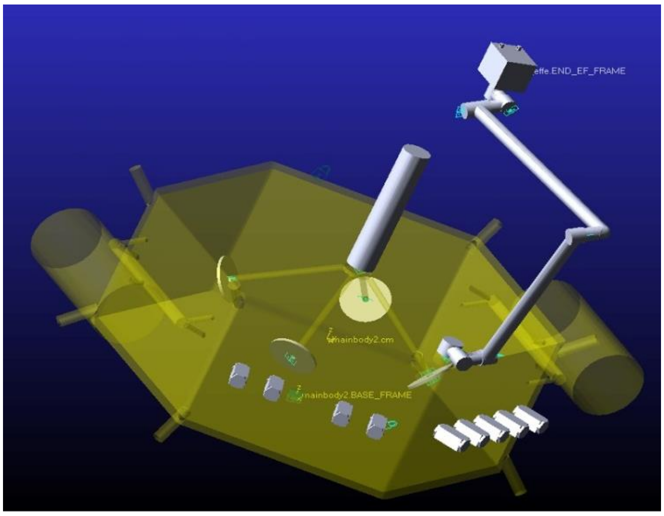


Figure 8: EROSS Servicer model in ADAMS.

To validate the performance of each robotic controller scheme, each control mode is implemented in the Matlab/ Simulink environment, communicating internally with the corresponding guidance mode, as well as with a developed model of the system in ADAMS. In ADAMS, the multi-body and contact dynamics of the system are modelled, thus simulating the controlled motion of the system, while also providing the required measurement inputs for the controller, to emulate the navigation sensors feedback. Fig. 8 illustrates the EROSS Servicer model in ADAMS. The Servicer platform is displayed as transparent, to display the platform reaction wheels pyramid configuration.

As an example, Fig. 9 shows the Simulink scheme of the AJSC control sub-mode, in which the connection with the system dynamics model in ADAMS is also shown (orange block at top-left of the figure). The block on the right-side of the figure is the autonomous joint-space controller, with the “measurements” from the ADAMS model. The desired trajectories in angles, rates and accelerations are generated from the “guidance trajectories” block at the bottom-left of the figure, acting as control references. The controller output is the required joint torque commands.

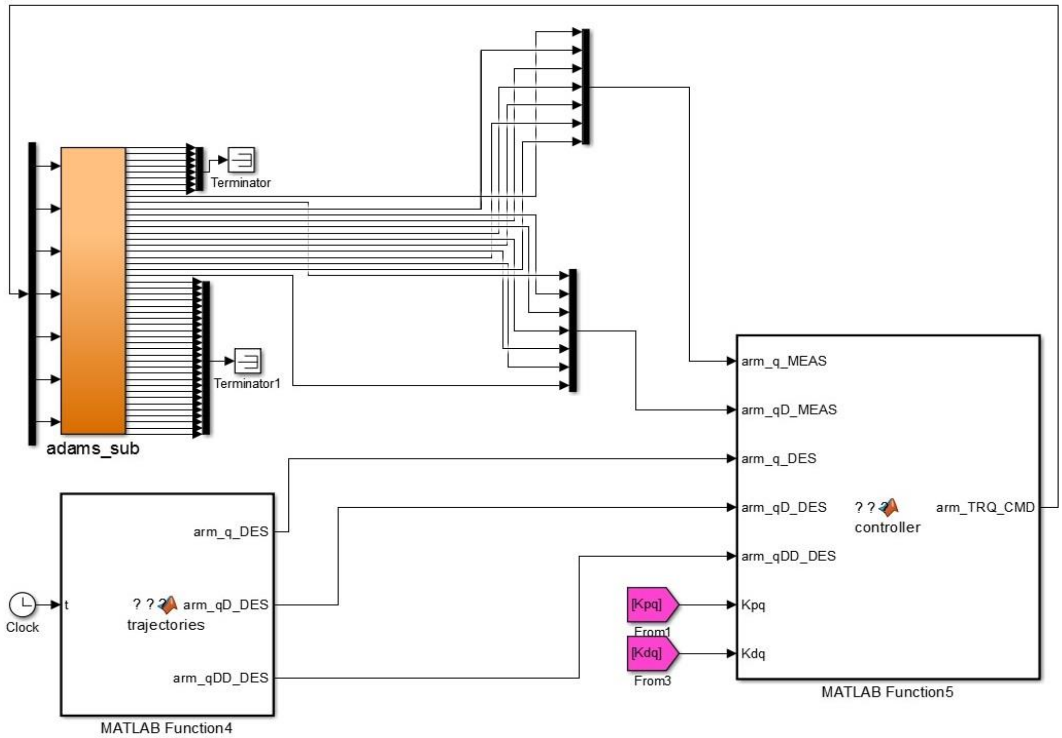


Figure 9: The Matlab/ Simulink model of the AJSC mode.

To validate the performance of the developed control schemes, a series of simulations was run in a hybrid Matlab/Simulink – ADAMS environment. The first layer in Matlab/Simulink was used to simulate the Control and Guidance modes, while the studied system dynamics were derived and propagated in the ADAMS model, providing as well the required "measurements" variables from the navigation modes. **The simulations validate the performances of the first three controllers (i.e., AJSC, CJSC, ICCC), while the RCCC validation is not presented hereunder to meet the paper length constraint.**

4.1 *AJSC control mode validation*

The first test was for the Autonomous Joint-Space Control mode (AJSC), so that the base is not controlled in a coordinated way. The initial joint angles were taken as follows

$$\mathbf{q}_{in} = [\ 0 \quad 0.3330 \quad 0.5742 \quad -2.2393 \quad -1.4767 \quad 3.4755 \quad 0\ ]^T\ rad$$

while the initial and final joint rates were all equal to zero. The desired joint angles were derived by fifth order polynomials desired trajectories, whose final joint angles constraints were

$$\mathbf{q}_{fin} = \mathbf{q}_{in} + [\ -20 \quad +15 \quad -20 \quad +20 \quad +10 \quad -10 \quad 0\ ]^T\ \text{deg}$$

Fig.10 shows, the joint errors obtained between the desired and the actual (measured) joint angles trajectories (i.e., $\mathbf{q}_{des} - \mathbf{q}$). The results show that an accuracy of 10^{-2}deg is reached at minimum on all joint control of the robotic arm. The Servicer platform angular velocities are shown in Fig. 11, to evaluate the impact of the robotic motion when no platform control was activated (i.e., the base was freely floating).

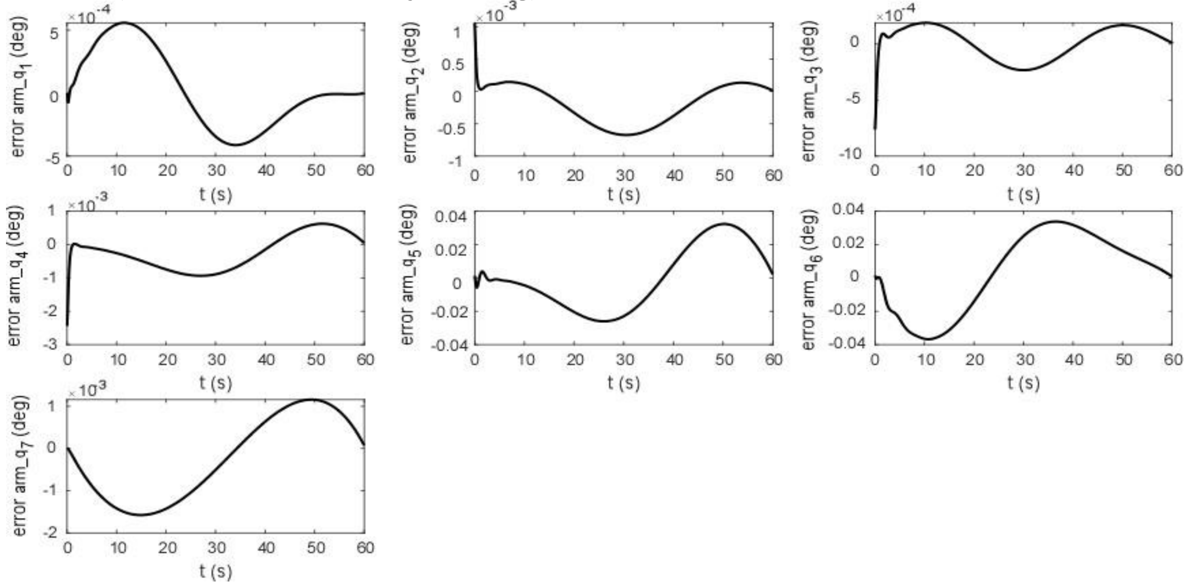


Figure 10: Joint angle errors during the AJSC validation test.

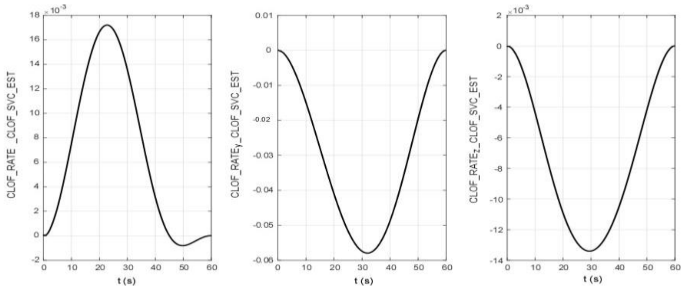


Figure 11: Servicer platform angular velocities during the AJSC validation test.

4.2 *CJSC control mode validation*

The second test was executed to validate the Coordinated Joint-Space Control mode (CJSC). The Robotic Arm initial angles and desired trajectories are the same as in the first test, but in this case the Servicer platform is controlled in a coordinated way, by a model-based PD control.

The initial Servicer platform Euler Parameters with respect to the inertial frame, were

$$\boldsymbol{\varepsilon}_{b\_in} = \begin{bmatrix} \varepsilon_{b1\_in} & \varepsilon_{b2\_in} & \varepsilon_{b3\_in} & \eta_{b\_in} \end{bmatrix} = \begin{bmatrix} 0.5 & 0.5 & -0.5 & 0.5 \end{bmatrix}$$

The corresponding desired Euler Parameter "trajectories" were to remain constant, while the initial Servicer platform angular velocities were all equal to zero, also required to remain constant during the test. Fig. 12 displays the joint errors (i.e., $\mathbf{q}_{des} - \mathbf{q}$), while Fig. 13 the Servicer platform angular velocities. Note that the attitude of the platform is actively controlled in this test as per the mode definition. In contrast with the AJSC tests presented above, the required Servicer base station keeping is maintained successfully in a coordinated way with the robotic arm controller.

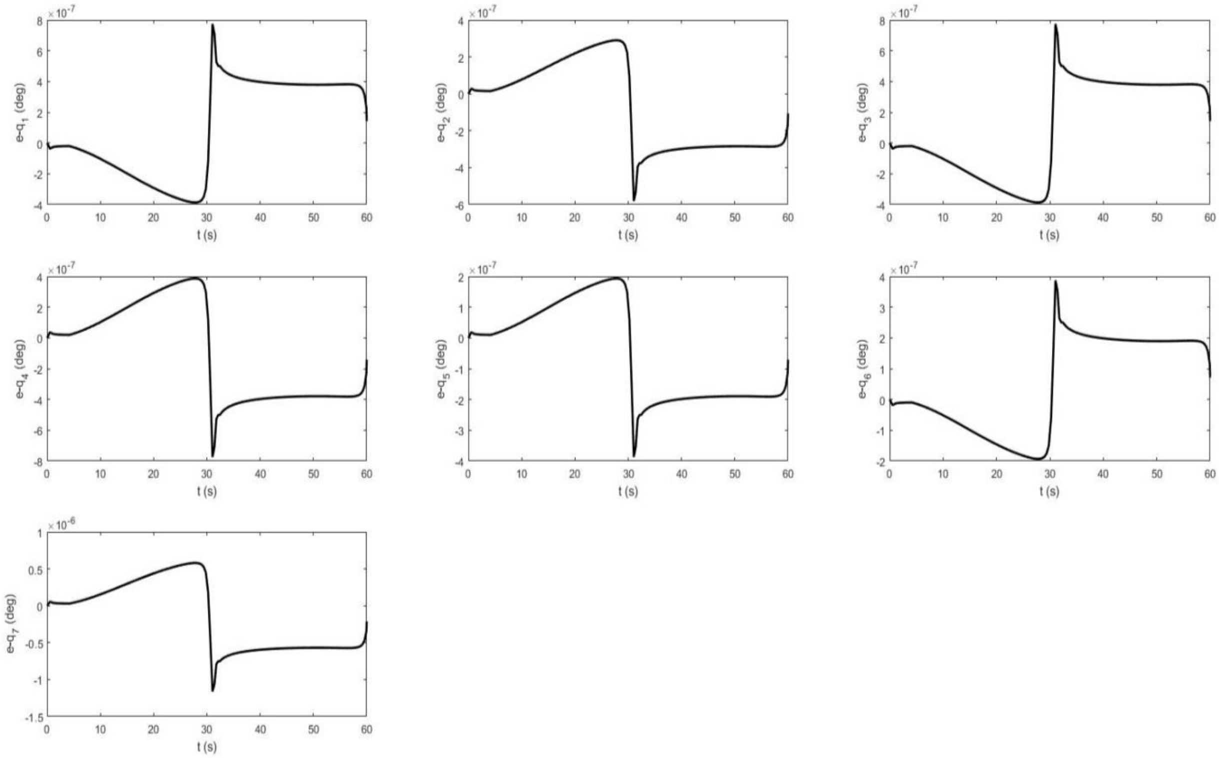


Figure 12: Joint angle errors during the CJSC validation test.

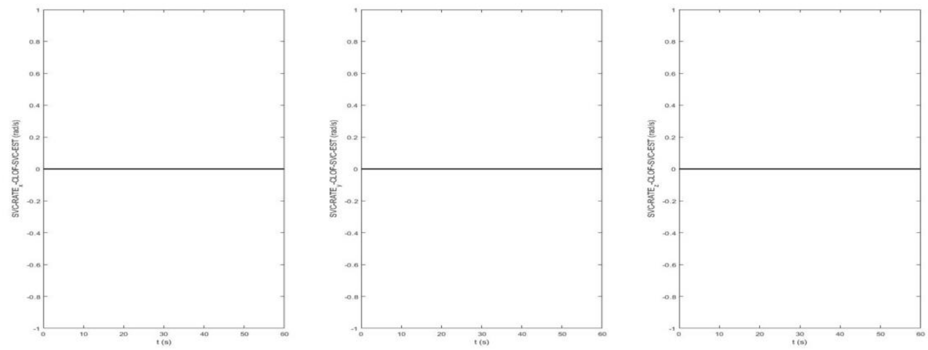


Figure 13: Servicer platform angular velocities during the CJSC validation test.

4.3 *ICCC control mode validation (trajectory tracking and compliant behaviour)*

The third test was for the Inertial Cartesian-space Compliant Control mode (ICCC), to demonstrate the trajectory tracking capabilities of the controller. The initial joint angles were

$$\mathbf{q}_{in} = [-1.5708 \quad 0.3330 \quad 0.5742 \quad -2.2393 \quad -1.4767 \quad 3.4755 \quad 0\ ]^T \ rad$$

while the initial and final joint rates were all equal to zero, resulting in a Cartesian-space initial displacement of the End-Effector from its desired goal pose, by

$$\Delta\mathbf{r}_{E\_in} = \left[0.06 \quad 0.96 \quad 0.06\right] m$$

as seen in the inertial frame. The initial Servicer platform Euler Parameters with respect to the inertial frame, were again

$$\boldsymbol{\varepsilon}_{b\_in} = \left[\varepsilon_{b1\_in} \quad \varepsilon_{b2\_in} \quad \varepsilon_{b3\_in} \quad \eta_{b\_in}\right] = \left[0.5 \quad 0.5 \quad -0.5 \quad 0.5\right]$$

The corresponding desired Euler Parameters "trajectories" were to remain constant for both Servicer platform and end-effector (attitude station-keeping), while the initial angular velocities which were all equal to zero, also were required to remain constant during the test (again for both Servicer platform and End-Effector). In this test, along with the Cartesian-space Compliant control scheme for the End-Effector motion control, the Servicer platform is also controlled in a coordinated way, by a model-based PD control.

Figs 14 and 15 show that the End-Effector position errors during the controlled trajectory tracking motion remain almost zero, validating the expected behaviour on the position and attitude tracking of both the end-effector and of the platform (N.B.: only the end-effector errors are presented for sake of paper length constraint).

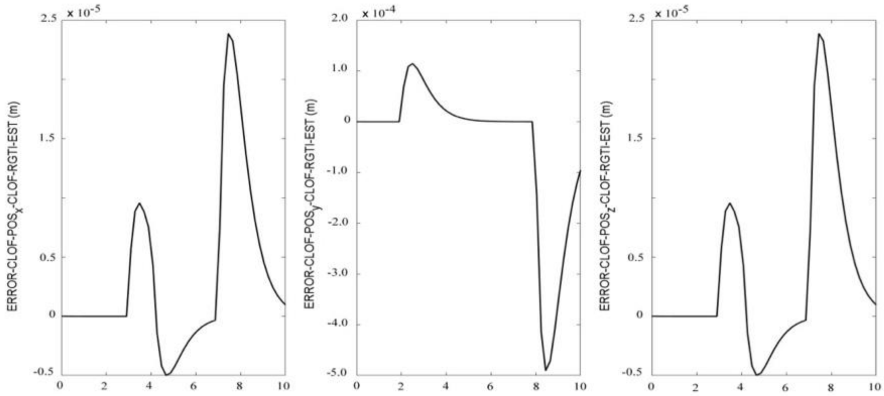


Figure 14: End-Effector position tracking errors during the ICCC validation test.

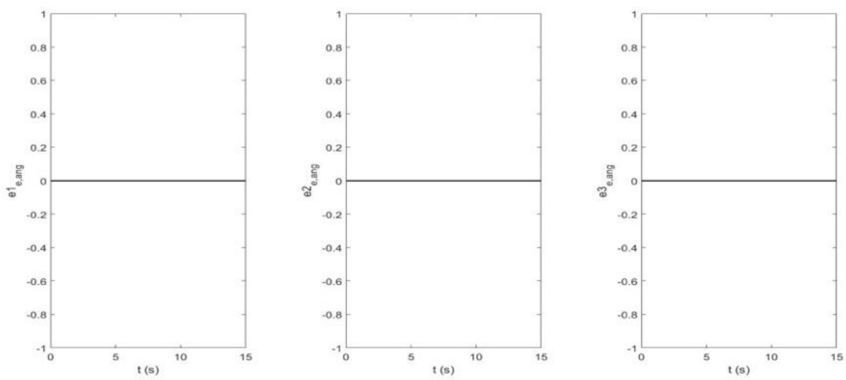


Figure 15: End-Effector attitude tracking errors $\boldsymbol{\varepsilon}_{EE}$ during the ICCC validation test.

A fourth test was carried out to validate the compliant behaviour of the ICCC mode. The initial position of the system, as well as its desired trajectories and End-Effector goal position are the same as previously. However, here a contact force is introduced and modelled as a spring force

$$\mathbf{Q}_f = \begin{bmatrix} 0 & -k_c \Delta y_c & 0 \end{bmatrix} N$$

acting on the End-Effector just before reaching its desired position, and at a distance of 1 cm from it, along the inertial y-axis, with Δy_c denoting the motion of the end-effector beyond the 1cm distance from the desired position (on the inertial y-axis), and k_c = 10 000. The Servicer platform is still actively controlled in a coordinated way, by a model-based PD control. However, in this case a non-zero desired trajectory for the Servicer platform attitude exists, to demonstrate the most challenging case: a coordinated control of end-effector motion with compliant behaviour during contact, coordinated with a Servicer platform attitude motion. The Servicer platform desired attitude trajectory consists of a trapezoidal profile on the angular velocity with constant angular acceleration of ±0.001 rad/s during the first/last 20 s of the simulation, with a constant velocity of 0.02 m/s during 5s in-between.

As shown in Fig. 16, the End-Effector absolute position error along the contact force axis is larger, with an error less than 10 mm, and remains constant after the contact, demonstrating the compliant behaviour of the End-Effector, while the errors remain below 2 mm on the other two axes despite the contact force coupling. The Servicer platform attitude is scarcely affected by the contact force at the end-effector thanks to the coordinated controller, demonstrating the expected compliance, see Fig. 17.

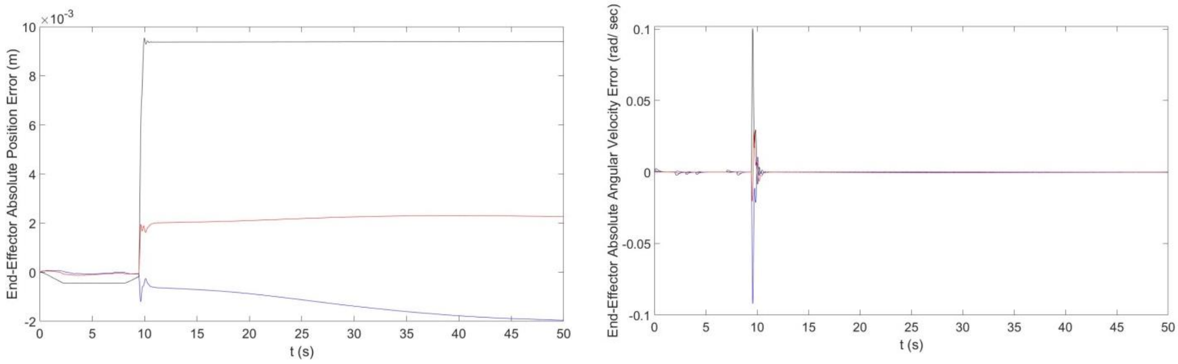


Figure 16: End-Effector position & rate errors during the compliant ICCC validation test.

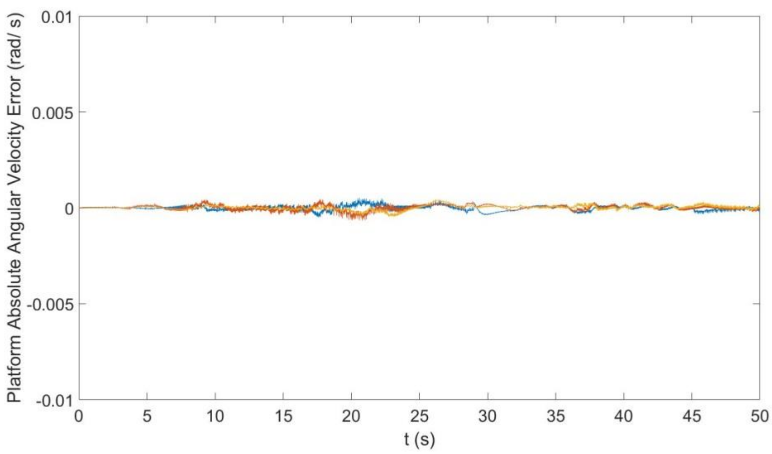


Figure 17: Servicer platform angular velocity during the compliant ICCC validation test.

5 CONCLUSION

The validation of a coordinated controller design in the scope of the EROSS project has been presented from the mission scenario to the coupled GNC architecture of the Servicer platform and robotic arm, along with the coordinated controller behaviour in multi-body simulation. The simulation results simulation validated the coordinated controller behaviour with joint or Cartesian-space trajectories, including a compliant behaviour when considering contacts at the robotic end-effector during grasping and servicing the Client vehicle. The mixed hardware/ software ground demonstration of EROSS has been carried out during April 2021 and is being processed to validate this GNC architecture.

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