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MARIO-LAND: a Multi-Arm Robot for In-orbit Operations at Laboratory for Autonomous Navigation Demonstrations

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Abstract

With the rapid expansion of space activities, sustainability has become paramount to mitigating orbital debris and supporting long-term operations. One promising approach is the development of infrastructure and systems assembled directly in orbit. Enabled by advanced space robotics, In-Orbit Servicing, Assembly, and Manufacturing (ISAM) is central to realizing these capabilities. To ensure mission reliability and maximize performance, ISAM technologies require thorough ground-based validation within controlled laboratory environments before orbital deployment.

To address this need, Cranfield University has developed a robotic platform—MARIO (Multi-Arm Robot for In-orbit Operations)—and a dedicated test facility—LAND (Laboratory for Autonomous Navigation Demonstrations)—to verify and validate ISAM hardware and control algorithms under space-analog conditions.

MARIO is a modular and reconfigurable robotic system designed for in-space servicing and assembly operations. It comprises three 6-degree-of-freedom manipulator arms mounted on a pneumatic floating base that glides over a polished epoxy floor, recreating a frictionless microgravity-like environment. The control system is built on ROS2, providing a robust and flexible framework for real-time coordinated multi-arm manipulation, trajectory planning, and dynamic collision avoidance.

Experimental tests have evaluated MARIO's performance in representative ISAM tasks, including docking, undocking, anchored motion, and the assembly of modular structures. Results demonstrate reliable and repeatable performance, showcasing MARIO's adaptability and capability to perform complex operations required in orbit. Data gathered from these experiments has been instrumental in refining control algorithms, improving locomotion stability, transition handling, and overall operational efficiency. The MARIO-LAND facility has proven effective for validating ISAM concepts and advancing ground-based testing methodologies.

Future work will focus on enhancing system autonomy through advanced navigation, improved sensing, and refined control strategies. These developments aim to increase the Technology Readiness Level (TRL) of MARIO and support the broader goal of advancing autonomous robotics for sustainable and scalable space operations.

Keywords: In-orbit Servicing, Assembly, and Manufacturing (ISAM), space robotics, multi-arm manipulation, ground-based testing, MARIO platform, LAND facility, ROS2 control architecture, modular structure assembly, space sustainability, space infrastructure

1. Introduction

Robotics and Technology for space is emerging as a cornerstone for enabling In-Orbit Servicing and Manufacturing (IOSM) and debris mitigation, addressing the growing demands of sustainable and reliable space operations. This paper introduces the MARIO Land facility, a free-floating multi-arm robotic testbed designed to bridge the gap between simulation and flight by enabling realistic experimentation for assembly, servicing, and debris capture tasks. The following sections will help us to understand the existing technologies in IOSM.

1.1. In-Space Operations

Space robotics forms the foundation for a broad range of essential on-orbit operations, such as rendezvous and docking, target capture, servicing, refueling, repairs, structural component replacement, crew rescue, and de-

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bris removal. Flores-Abad *et al.* provide a comprehensive overview of on-orbit servicing (OOS) missions and enabling technologies [1]. Real-world missions like Northrop Grumman's MEV-1 for life extension [8], NASA's Restore-L/OSAM-1 (Spider) [9], and DARPA's RSGS [10] illustrate practical deployment of robotic servicing systems in GEO. These missions highlight stringent requirements for robotic dexterity, robust autonomous control, and reliable sensing, emphasizing the need for preflight testing under realistic conditions [1].

1.2. Space Sustainability through IOSM

Orbital congestion and debris proliferation present escalating risks to long-term space sustainability. Although regulatory frameworks such as UNCOPUOS Long-Term Sustainability guidelines [12] and IADC debris mitigation policies [13] exist, they are largely voluntary. IOSM (In-Orbit Servicing and Manufacturing) methodologies, including satellite life extension, refuelling, and in-orbit repair, are central to achieving a circular space economy—extending satellite lifetime and reducing the need for decommissioned launches [1, 3]. Jongjittanon emphasizes IOSM's role in enabling a circular value chain in orbit [3]. Commercial efforts, such as MEV [8] and Orbit Fab [11], demonstrate viable paths toward sustainable operations via services like on-orbit refuelling.

1.3. In-Space Assembly with Robotics

Robotic in-space assembly (ISA) offers a scalable approach to constructing large structures that exceed payload fairing constraints. Wang *et al.* note that robotic OASR (On-Orbit Assembly with Space Robots) is essential for constructing infrastructure, servicing, and enabling future space systems [2]. Historical efforts such as Orbital Express and Robotic Refueling Mission (RRM) aboard ISS proved key robotic servicing capabilities [1]. ISA supports modular construction of expansive systems—like telescopes or solar arrays—delivered in parts and assembled in orbit, enabling flexible, upgradable missions with reduced launch mass constraints [1, 2].

1.4. Debris Management or Capture using Space Robotics

Active Debris Removal (ADR) is essential for preserving orbital safety. Methods span both contact-based approaches—such as robotic arms, nets, and harpoons—and contactless techniques, including electrodynamic tethers, drag sails, and laser ablation [4]. Bigdeli *et al.* categorize current mechanisms—robotic capture, nets, harpoons, tethers, and drag devices—for debris mitigation [4]. Remove DEBRIS, with its net and harpoon demonstration in low Earth orbit, highlights practical challenges and dynamics involved in capturing non-cooperative targets [14]. Mavrakis *et al.* quantified grasp stability and force control, essential for safe capture of tumbling objects [5]. Robotics enables dexterous, controlled engagement with debris, but requires advanced force control and contact modeling to avoid imparting adverse reaction forces on the servicing platform [19].

1.5. Current Research Facilities and Test Beds

Ground-based analogs are indispensable for validating IOSM and ADR technologies prior to orbital flight. Air-bearing platforms on frictionless floors (epoxy, granite, glass) closely approximate microgravity conditions by supporting near-frictionless planar motion [6, 7]. ESA's ORBIT facility offers a 45 m^2 epoxy floor with high-precision motion capture for testing rendezvous, debris capture, and contact operations [6]. The SOOST testbed at NUAA in China uses a granite table (5×10 m) to support formation dynamics experiments under precise planar tracking [17]. GNC and dynamic response testing—including thruster and force-torque behaviors—are facilitated by such controlled environments.

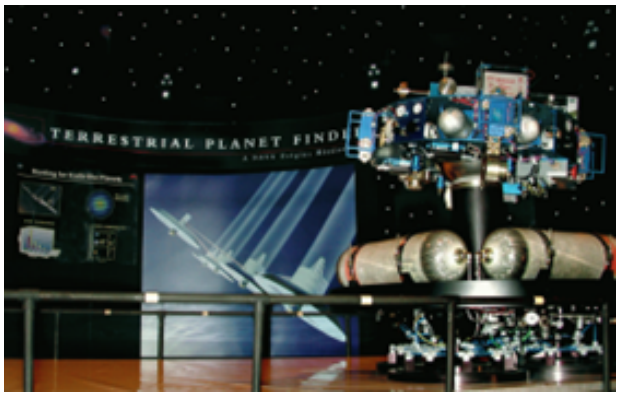

Figure 1: NASA JPL 5DOF Formation Flying Test Bed

Lab-scale platforms like NASA JPL's SSDT testbed offer complementary capabilities for thruster simulation and autonomous formation control [18]. Such facilities remain limited in scaling to full 6-DoF, multi-arm manipulations.

1.6. State-of-the-Art Facilities

Leading institutions have developed rich testbeds for IOSM/ADR technology maturation. The University of Surrey's STAR Lab integrates air-bearing tables and robotic arms for six-DoF free-flying manipulation—informing the development of net-harpoon capture systems deployed on Remove DEBRIS [14, 15]. ESA's ORBIT testbed employs onboard air-bearing platforms (ACROBAT, MANTIS) with integrated Vicon tracking for docking and contact operations [6]. DLR's TEAMS/EPOS facilities offer granite surfaces and multi-axis thruster-based platforms to simulate orientation and translation

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dynamics with high fidelity [16]. Other facilities like ADAMUS (Florida), Yonsei's ASTERIX, University of Würzburg's glass-floor testbeds, and Luxembourg's Zero-G Lab provide diverse DoF capabilities and tracking systems (OptiTrack, ultrasonic), improving experimental generality [4, 6]. However, there remains a lack of free-floating multi-arm robotic systems with force-torque sensing integrated into ROS2-based, coordinated control platforms.

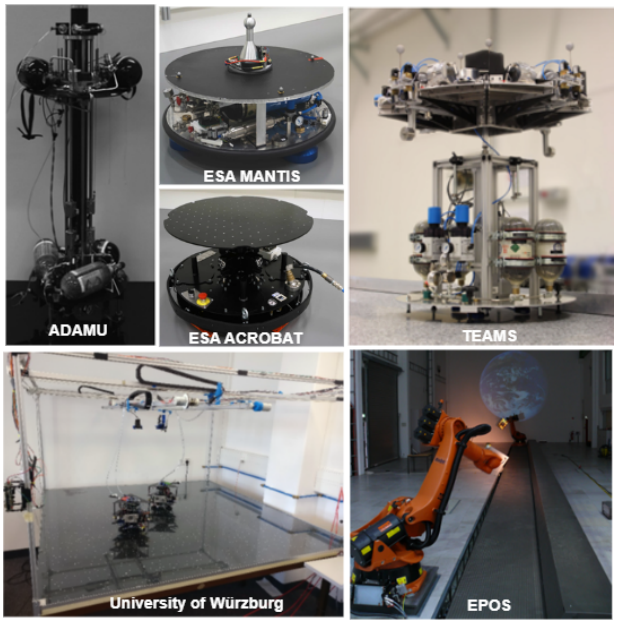

Figure 2: IOSM Testbeds and Platforms

1.7. Current Gaps and Motivation for MARIO Land

While existing testbeds support planar or single-arm experiments, few enable multi-arm coordination on free-floating platforms with high-fidelity force-torque sensing and real-time control. MARIO Land at Cranfield University fills this niche: a three-arm robot on an air-bearing base over an epoxy floor, integrated with ROS2 for coordinated manipulation and equipped with force-torque sensors and motion tracking [6, 19]. This setup enables realistic emulation of multi-arm tasks like docking, assembly, debris capture, and tool-exchange, with instrumentation to quantify force–deflection dynamics and platform locomotion.

1.8. Impact on ISOM and Debris Capture Research

MARIO Land's experiments and results provide insights on how manipulator force inputs correlate with base deflection, velocity, and trajectory—information central to validating dynamic models and improving control algorithms, such as impedance control and model predictive control (MPC) [5, 19]. By demonstrating repeatable and predictable responses in space-analog conditions, MARIO Land enhances astronautic system TRLs and helps bridge the gap between simulation and flight. The platform's insights feed into mission design, autonomous operation validation, and risk assessment for future ISAM and debris-capture missions.

2. Research Facilities and Equipment at ASTRA-Lab

The experiments presented in this work were conducted in the **Advanced Space Technology and Robotics for Astronautics (ASTRA)** laboratory at Cranfield University. The facility houses the MARIO LAND testbed, designed to support ground-based emulation of space-like dynamics for research in In-Orbit Servicing and Manufacturing (IOSM) and debris capture missions. The key objective of MARIO LAND is to provide a controllable, repeatable, and measurable environment for validating robotic control strategies, multi-arm coordination, and interaction dynamics between free-floating systems in microgravity-analogue conditions.

2.1. MARIO

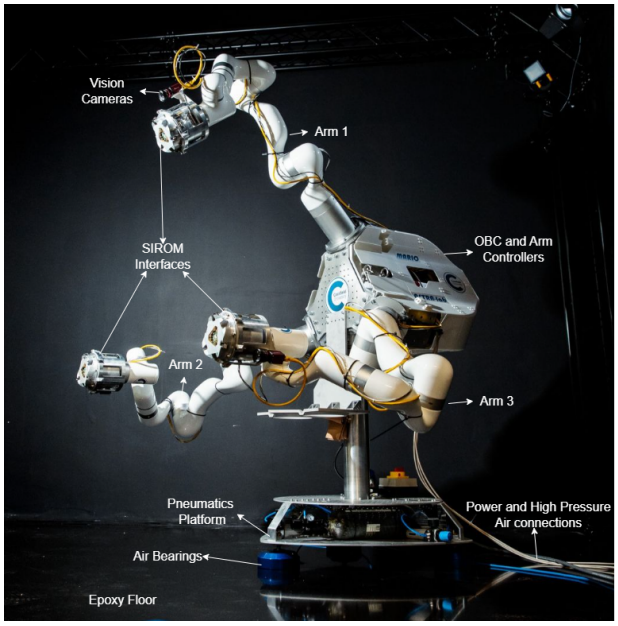

Figure 3: MARIO Robotic Platform

MARIO (Multi-Arm Robot for In-Orbit operations), shown in Figure 3, is a reconfigurable, air-bearing-supported robotic platform equipped with three 6-DOF manipulators, each integrated with a force/torque sensor at the wrist. The platform's modular architecture supports rapid adaptation for different mission scenarios, including cooperative assembly, tool manipulation, and contact-based servicing tasks. The arms can operate in coordinated

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or independent modes, enabling complex manipulation strategies such as dual-arm grasping, assembly with active base compensation, and force-controlled interactions with other floating bodies. MARIO is integrated with the ROS 2 Humble framework, leveraging MoveIt 2 for motion planning and custom impedance control schemes for contact dynamics. Control experiments in MARIO LAND focus on measuring reaction forces induced by manipulator contact and correlating them with base motion, to refine control algorithms for real-world IOSM missions.

2.2. LAND

The LAND (Locomotion and Navigation Demonstrator) platform refers to the underlying air-bearing base system supporting MARIO and other free-floating payloads in the laboratory. The platform is supported by high-pressure air jets that lift it above the epoxy floor, creating a nearly frictionless planar environment. This setup allows the simulation of orbital relative motion dynamics without the disturbances of rolling friction, enabling accurate testing of multi-body dynamics, control laws, and autonomous navigation algorithms in two degrees of freedom (X, Y) plus yaw rotation. The LAND system allows for testing multiple payloads and technologies, including satellite mock-ups for navigation experiments, robotic arms for servicing demonstrations, and cooperative multi-agent configurations for docking and assembly studies.

Figure 4: LAND and VICON systems

2.2.1. Tracking System

LAND is equipped with a **Vicon** optical motion capture system as shown in Figure 4, providing sub-millimeter accuracy in tracking the pose of all moving bodies in the test area. Retroreflective markers are placed on MARIO, the LAND base, and any interaction targets, enabling real-time kinematic data acquisition at high frequency. Accurate tracking is essential for linking manipulator-induced forces to the translational and rotational behavior of free-floating platforms, and for verifying model-based predictions of contact dynamics.

2.2.2. Epoxy Floor

The laboratory floor is coated with a precision-leveled, low-friction epoxy resin surface as shown in Figure 5, designed to provide a uniform and smooth environment for air-bearing operations. The frictionless nature of the epoxy floor is essential for reproducing the unconstrained drift and rotational motion characteristic of orbital systems. Regular maintenance ensures surface flatness within tight tolerances, minimizing disturbances to platform motion. The combination of the epoxy floor and air-bearing supports yields a planar motion environment that closely emulates microgravity translation and rotation, making it possible to study long-duration drift, collision dynamics, and low-force interactions in a controlled, repeatable manner.

Figure 5: LAND EPOXY floor

2.3. Model Spacecraft Platforms

In addition to the MARIO system, the ASTRA LAB hosts a range of free-floating spacecraft simulators mounted on air-bearing platforms. These platforms replicate the dynamics of satellites in orbit, including translational and rotational degrees of freedom, enabling realistic testing of proximity operations, docking maneuvers, and interaction with servicing robots. The platforms can be outfitted with mock-up payloads, such as solar arrays, docking adapters, and representative debris geometries, to recreate operational scenarios. Combined with the Vicon tracking system, these platforms allow for performing precise motion analysis, collision detection, and trajectory estimation, forming the basis for validating guidance, navigation, and control (GNC) algorithms in a controlled microgravity-analogue environment.

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3. Research Application

By combining free-floating base dynamics with multi-arm manipulation and precise sensing, MARIO LAND enables the safe and realistic testing of robotic operations that are otherwise difficult to replicate and test on Earth. The following subsections outline key application areas where MARIO contributes to current and future space missions.

3.1. In-Space Assembly

The MARIO LAND facility aims to enhance the process of developing and validating robotic technologies for in-space assembly. The capability to operate multi-arm systems in a frictionless environment enables accurate reproduction of assembly tasks such as structural truss construction, payload deployment, and modular component integration. In particular, MARIO's impedance-controlled manipulators can simulate delicate contact scenarios, ensuring assembly operations maintain structural integrity while compensating for base motion induced by manipulator forces. The experiments directly support mission concepts like the European Space Agency's (ESA) *In-Space Assembly of Spacecraft and Components* (ISAAC) initiative, providing a low-risk testing environment before on-orbit deployment.

3.2. Space Sustainability with In-Space Servicing

In-space servicing (ISS) capabilities, including refueling, maintenance, relocation, and end-of-life deorbiting, are key enablers of long-term space sustainability. MARIO LAND allows for realistic emulation of such servicing operations through the interaction of free-floating platforms in a planar microgravity analogue. Using force/torque feedback, the system can assess the stability and safety of contact operations while ensuring minimal risk of secondary debris generation. This research directly contributes to the broader vision of reducing space debris, extending spacecraft lifetimes, and maintaining the usability of valuable orbital slots.

3.3. Industrial Experiments

The ASTRA LAB supports collaborative industrial experiments with agencies and commercial partners to advance IOSM technologies from concept to pre-flight readiness.

3.3.1. In-Space Assembly using MARIO – ISAAC

One key project supported by MARIO LAND is the **ISAAC** mission simulation, where MARIO's multi-arm setup is employed to test robotic assembly of large modular structures as shown in 6. The frictionless testbed environment accurately replicates the disturbance effects on the servicing platform during manipulation. Data from these tests help refine predictive control algorithms, ensuring high-precision assembly under realistic dynamics. The Vicon motion capture system is used to track component trajectories and platform drift, while the force/torque sensors validate model predictions of interaction forces.

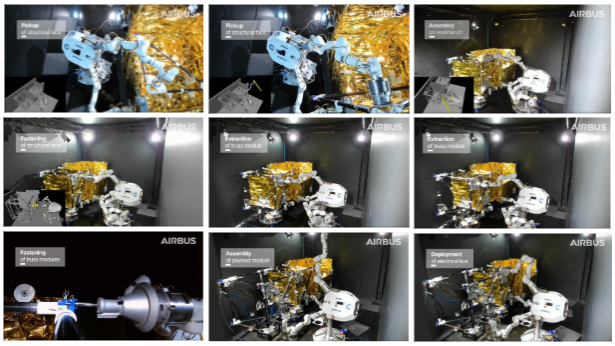

Figure 6: ISAAC project, Credits - AIRBUS Defense and Space

3.4. Research Experiments

Beyond industrial collaborations, MARIO LAND enables fundamental research into contact dynamics, cooperative manipulation, and space robot autonomy.

3.4.1. Contact Dynamics with In-Orbit Capturing and Servicing

The experiments in the MARIO LAND facility were designed to investigate how manipulator activity influences the free-floating dynamics of the MARIO platform, with a focus on base oscillations and interaction forces during contact events. Using air-bearing platforms to emulate satellite motion in orbit, three distinct cases were examined.

Case 1: Influence of Single-Joint Motion on MARIO's Base

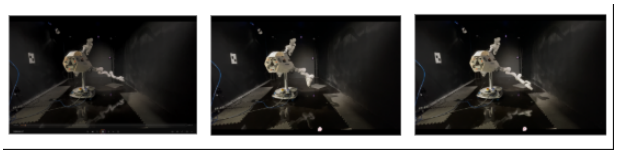

Figure 7: MARIO Joint Actuation Effect on Base

When one of MARIO's manipulator joints was actuated in free space (i.e., without external contact), the generated joint torques induced reactive forces on the base as shown in Figure 7. Due to MARIO's free-floating configuration, these reactions caused measurable oscillations and displacements of the base. The experiments showed that the magnitude and frequency of base motion were directly dependent on which joint was actuated, its velocity

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profile, and the arm's inertia distribution. This case served as a baseline to characterize how internal manipulator dynamics alone can destabilize the platform.

Case 2: Contact with a Stationary Target

Figure 8: MARIO Interaction with Stationary Platform

In this scenario Figure 8, MARIO's arm approached and interacted with a target platform fixed in place. Upon contact, the impedance-controlled arm transmitted interaction forces back into the base, resulting in oscillatory motion despite the target being immobile. The force–torque sensors captured the reaction loads at the end-effector, while motion capture tracked how these translated into base disturbances. The results highlighted how the balance between arm compliance and joint torques determined MARIO's stability when contacting rigid, stationary structures in orbit.

Case 3: Contact with a Moving Target

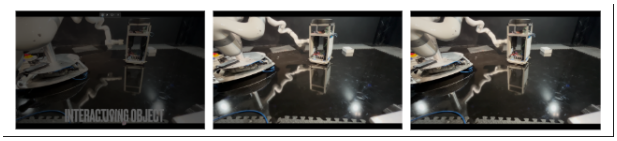

Figure 9: MARIO Interaction with Moving Platform

The third scenario involved contact with a free-floating mock-up satellite mounted on air bearings. Here, Figure 9 both MARIO and the target platform were free to drift in response to interaction forces. Contact dynamics became more complex, as the forces generated by the manipulator not only disturbed MARIO's base but also altered the trajectory of the target. In several trials, corrective arm motions amplified the coupled oscillations between the two bodies, demonstrating the challenges of capturing or servicing a moving object in orbit. This case provided valuable insights into multi-body coupling effects that occur during real on-orbit servicing operations.

4. Results and Discussion

The results are presented in two parts. First, the lessons learned from the final demonstration of the ISAAC project are summarized, highlighting the performance of MARIO in supporting in-space assembly concepts. Second, experimental findings on contact dynamics within the MARIO LAND facility are discussed, focusing on how manipulator activity influences base oscillations and how MARIO interacts with both stationary and free-floating target platforms. Together, these results provide valuable insights for advancing robotic strategies in future in-orbit servicing and assembly missions.

4.1. Lessons Learnt from ISAAC

Ground-based testing of In-Orbit Servicing and Manufacturing (ISAM) scenarios at the ASTRA Laboratory, using the MARIO LAND facility, has provided valuable insights into improving the fidelity and repeatability of laboratory simulations. Lessons learned from the ISAAC project have informed refinements to the test environment and operational procedures.

4.1.1. Docking Interface Stability

Legacy docking interfaces exhibited oscillations during locomotion and contact tasks due to minor alignment tolerances. Updated designs with improved mechanical stability reduced oscillatory motion and enhanced performance in force-controlled docking scenarios.

4.1.2. Control System Integration

Separation of the MARIO control stack from the Ground Control Station (GCS) improved ROS 2 network stability and eliminated communication conflicts. This modular approach also better reflects spacecraft-to-ground control architectures for ISAM operations.

In Addition to these, MARIO also requires a fully functional Impedance control to handle tool and object interaction when the air bearing platform is turned on. This will help in adapting to the forces acting towards the end effector and how it is propagated to the base of MARIO during its floating period.

Overall, these lessons emphasize the need for refined environmental control, adaptable planning capabilities, and modular integration approaches to increase the representativeness and efficiency of ground-based ISAM simulations.

4.2. Preliminary results from Contact Dynamics

The experiments conducted in the MARIO LAND facility produced quantitative insights into how manipulator activity affects the free-floating dynamics of MARIO and its interaction with satellite mock-ups. Two sets of representative results are presented below.

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4.2.1. *Influence of Single-Joint Motion on MARIO's Base*

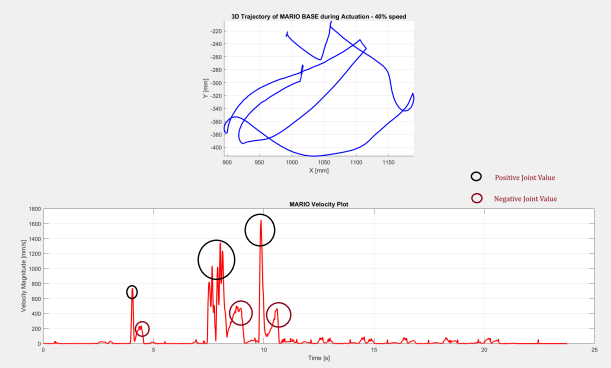

Figure 10: MARIO Joint Torque effect on MARIO Base

The first set of results investigated how the actuation of a single manipulator joint induced oscillations and displacements in the free-floating base of MARIO.

3D Base Trajectories: The recorded trajectories Figure 10 demonstrated that even isolated joint movements caused measurable drift of MARIO's base. The displacement magnitude increased with the commanded joint velocity, indicating a clear coupling between manipulator motion and base disturbance.

Base Velocity Profiles: Velocity plots showed that higher joint actuation speeds led to sharper peaks in MARIO's translational and rotational velocities. These results confirm that base oscillations are strongly dependent on the arm's actuation dynamics and that the inertia distribution of the system amplifies disturbances at higher joint velocities.

Overall, these findings provide a baseline characterization of how internal manipulator torques propagate through the floating base, establishing the dynamic sensitivity of MARIO prior to external contact events.

4.2.2. *MARIO–Mushroom Platform Interaction*

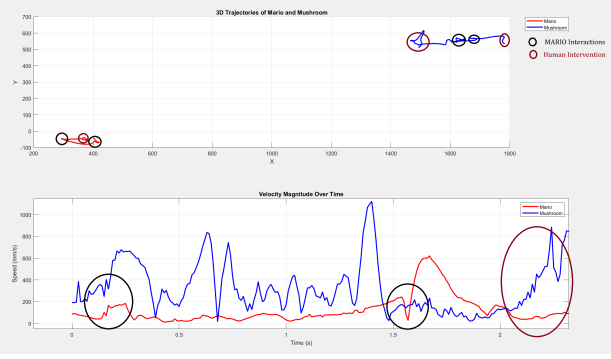

Figure 11: MARIO's interaction with Mushrooms platform results

The second set of results focused on contact dynamics when MARIO's arm established contact with the Mushroom platform, which was mounted on air bearings to replicate a free-floating satellite.

Relative 3D Trajectories: The motion capture data Figure 11 revealed that upon contact, both MARIO and the Mushroom platform exhibited noticeable deviations from their pre-contact trajectories. The magnitude of drift was dependent on the approach velocity and compliance settings of MARIO's impedance controller.

Velocity Coupling: Velocity plots showed correlated changes in both platforms' dynamics at the moment of contact. MARIO's base experienced oscillatory velocity profiles, while the Mushroom platform exhibited corresponding reactive motions, confirming the bi-directional coupling between the two free-floating bodies.

These results highlight the nonlinear and coupled nature of free-floating contact dynamics. Even small interaction forces led to significant deviations in both MARIO and the target's motion, underscoring the importance of predictive modeling and control strategies that explicitly account for base disturbances during servicing tasks.

4.3. *Discussion*

The ISAAC project, conducted within the ASTRA Lab using the MARIO LAND facility, has provided valuable insights into the execution of in-space assembly (ISA) operations under controlled ground-based conditions. By replicating free-floating dynamics on the epoxy-floored air-bearing platform, ISAAC experiments enabled the evaluation of robotic manipulation strategies for structural assembly in a microgravity analogue. Key achievements included refining docking and alignment techniques, validating autonomous motion planning under varying constraints, and improving the resilience of visual servoing systems against environmental disturbances. These advancements have demonstrated the feasibility of complex on-orbit assembly tasks while providing a controlled framework to test operational robustness and adaptability.

Building on operational insights from ISAAC, the research on contact dynamics has concentrated on the early stages of in-orbit capture and servicing. In this setup, MARIO engages with a free-floating mock-up satellite placed on mini air-bearing platforms, allowing for precise measurement of force–torque data at the robot's end-effector and the resulting drift responses of both platforms. By correlating the applied forces with relative velocities and trajectories recorded by the Vicon tracking system, the experiments have provided a deeper understanding of momentum exchange and transient interaction forces under microgravity-like conditions. These results support the development and validation of impedance control and Model Predictive Control (MPC) strategies to achieve safe, stable, and predictable capture of non-cooperative targets.

From a debris removal perspective, this methodology

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lays the groundwork for simulating the dynamics of engaging with irregular or tumbling objects. The controlled environment of MARIO LAND allows for safe testing of various approach, capture, and stabilisation strategies before on-orbit deployment. Insights from these tests help in designing algorithms that adapt to uncertain target motion, improve capture precision, and reduce the risk of mission failure in debris mitigation operations.

5. Conclusion

Results from ISAAC's in-space assembly experiments, together with contact dynamics studies related to capture, servicing, and debris removal, highlight the role of high-fidelity ground-based testing in advancing In-Orbit Servicing and Manufacturing (ISAM) technologies. The MARIO LAND facility, with its frictionless epoxy floor, air-bearing platforms, and integrated tracking and sensing systems, offers a unique capability to replicate microgravity conditions for multi-faceted ISAM research.

Incorporating ISAAC's operational lessons into subsequent contact dynamics trials has improved stability, repeatability, and adaptability of experimental campaigns. This iterative development process bridges the gap between simulation and operational readiness, enabling the validation of control strategies and robotic behaviours under representative dynamic conditions. As the ASTRA Lab expands its scope to include multi-contact servicing, cooperative multi-robot operations, and complex debris removal scenarios, MARIO LAND will remain a cornerstone for maturing ISAM technologies, ultimately contributing to the sustainable use of orbital infrastructure and the mitigation of space debris.

References

[1] A. Flores-Abad *et al.*, "A review of space robotics technologies for on-orbit servicing," *Prog. Aerospace Sci.*, vol. 68, pp. 1–26, 2014.

[2] Z. Wang *et al.*, "Review of On-Orbit Assembly Technology with Space Robots," *Aerospace*, vol. 12, no. 5, art. 375, 2025.

[3] N. Jongjittanon, *Contribution of In-Orbit Servicing on Space Sustainability*. Ph.D. thesis, Chaire-Sirius, 2022.

[4] M. Bigdeli *et al.*, "Mechanics of Space Debris Removal: A Review," *Aerospace*, vol. 12, no. 4, art. 277, 2025.

[5] N. Mavrakis *et al.*, "On-Orbit Robotic Grasping of a Spent Rocket Stage," *Frontiers Robot. AI*, vol. 8, art. 652681, 2021.

[6] European Space Agency, "Zero-G testing on Europe's flat-test floor," *ESA News*, 17 Jul. 2024.

[7] Z. Huang *et al.*, "Characterizing an Air-Bearing Testbed for Simulating Spacecraft Dynamics and Control," *Aerospace*, vol. 9, no. 5, art. 246, 2022.

[8] Northrop Grumman, "Mission Extension Vehicle (MEV-1)," Press Release, 2020.

[9] NASA, "OSAM-1 (Spider)," Mission Brief, 2022.

[10] DARPA, "RSGS Program Overview," 2023.

[11] Orbit Fab, "On-Orbit Refuelling Services," 2024.

[12] United Nations COPUOS, "Long-Term Sustainability Guidelines," 2019.

[13] IADC, *Space Debris Mitigation Guidelines*, 2019. Available at: https://www.unoosa.org/res/oosadoc/data/documents/2025/aac_105c_12025crp/aac_105c_12025crp_9_0_html/AC105_C1_2025_CRP09E.pdf

[14] C. Taylor *et al.*, "RemoveDEBRIS: on-orbit demonstration," IAC 2018.

[15] N. Mavrakis, D. Zhou Hao, and Y. Gao, "On-Orbit Robotic Grasping of a Spent Rocket Stage: Grasp Stability Analysis and Experimental Results," *Frontiers in Robotics and AI*, vol. 8, p. 183, June 2021. DOI: 10.3389/frobt.2021.652681. Licensed under CC BY 4.0.

[16] DLR, "TEAMS/EPOS Facility Description," 2021. Available at: https://www.dlr.de/en/research-and-transfer/research-infrastructure/european-proximity-operations-simulator-epos

[17] Z. Huang, W. Zhang, T. Chen, and D. Jin, "Characterizing an Air-Bearing Testbed for Simulating Spacecraft Dynamics and Control," *Aerospace*, vol. 9, no. 5, p. 246, May 2022. DOI: 10.3390/aerospace9050246. Licensed under CC BY 4.0.

[18] D. Barnhart *et al.*, "Development of a micro-satellite dynamic test facility," 2009.

[19] A. Flores-Abad, "Robotic Manipulation in Free-Flying Environments," *J. Space Robotics*, vol. 5, no. 2, pp. 100–117, 2020.

[20] ESA, "ADR Roadmap and Priorities," ESA Tech Note, 2023.

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