A PLANAR AIR-BEARING MICROGRAVITY SIMULATOR FOR VALIDATION OF ROBOTIC CAPTURE OPERATIONS

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ABSTRACT

A significant number of In-Orbit Servicing (IOS) and Active Debris Removal (ADR) missions will rely on the use of manipulators for the capture operation. Robotic systems can be validated in simulated microgravity conditions on air-bearing test-beds. This paper presents the planar microgravity simulator at the Space Research Centre of the Polish Academy of Sciences. The test-bed is based on a granite plate. The mock-up of the satellite-manipulator system mounted on air-bearings moves on the plate's surface. Recently added elements include the gripper and the target satellite mock-up. With these elements, the entire operation of capturing a rotating target can be simulated. The presented results show the new capabilities of the test-bed and its potential for validating the technologies required for IOS and ADR.

1. INTRODUCTION

In recent years, the development of technology in the field of space robotics has been driven, among other factors, by the needs of planned Active Debris Removal (ADR) and In-Orbit Servicing (IOS) missions [1, 2]. These missions will rely heavily on the use of robotic manipulators for in-orbit capture and servicing tasks [3, 4]. Advanced robotic technologies are also required for in-orbit assembly and maintenance of large orbital structures [5]. Experimental validation of robotic systems is essential to ensure that these systems will operate properly in the orbital environment. One of the major challenges is that testing is performed under Earth's gravity conditions, while during the orbital mission, the robotic system will be working in microgravity. Thus, various approaches are used to simulate microgravity conditions [6-8]: hardware-in-the-loop tests based on industrial manipulators, suspension systems, parabolic flights, drop towers, underwater tests with neutral buoyancy vehicles and air-bearing microgravity simulators. The air-bearing simulators are particularly popular, among other reasons, due to their ability of emulating the dynamic behaviour of the free-floating satellite-manipulator system, low disturbances and low operating costs [9].

An air-bearing test-bed is based on a flat and precisely levelled surface (granite plate, glass panels or epoxy floor). The mock-up of the satellite-manipulator system is mounted on planar aerostatic air-bearings and placed on the test-bed surface. Air-bearings utilize a thin film of pressurized gas to provide frictionless translational and rotational motion on the surface. As a result, microgravity conditions are simulated in two dimensions (with motion limited to the horizontal plane). Possible applications of planar air-bearing microgravity simulators include testing manipulator hardware, conducting experiments related to close proximity operations and formation flight, validation of manipulator trajectory planning and control algorithms and research related to manipulator flexibility and the dynamics of the docking operation.

The planar air-bearing microgravity simulator at the Space Research Centre of the Polish Academy of Sciences (Centrum Badań Kosmicznych Polskiej Akademii Nauk, CBK PAN) is in operation since 2012 [10] and allows for conducting various experiments in the field of space robotics. This test-bed has been used in multiple national and international research projects. It has also been used in several projects funded by the European Space Agency (ESA), including Sample Acquisition Means for the Phootprint Lander: Experiments and first Realisation (SAMPLER) [11] and e.Deorbit Phase B1 [12]. Research conducted on the air-bearing microgravity simulator at CBK PAN includes the verification of a control strategy for a space robot conducting rendezvous manoeuvres [13], demonstration of simultaneous control of a free-flying chaser satellite and its manipulator [14], validation of collision-free trajectory planning methods applicable for a free-floating manipulator [15, 16], experiments related to optimal trajectory planning [17] and realization of manipulator trajectories that avoid dynamic singularities [18].

Several major improvements to the air-bearing test-bed at CBK PAN have been made over the years. In the years 2015 – 2016, a new mock-up of the chaser satellite equipped with cold-gas thrusters was developed and an external vision system was added to allow closed-loop control of the satellite and end-effector position in the Cartesian space [19]. In the years 2017 – 2019, an additional kinematic pair was added to the manipulator and new PCB boards for the main computer, joints controllers, and cold-gas thrusters were developed [20]. Moreover, a new application with intuitive user interface was developed to enable easier control of the experiments conducted on the test-bed.

This paper focuses on the latest upgrade of the test facility at CBK PAN, which was introduced in the framework of the project "Development and Validation of a Control System for Space Manipulator" (SpaRoC), funded by the Polish National Centre for Research and Development (NCBiR). New elements added to the test-bed include: (i) a Modular Gripper mounted on the manipulator end-effector, and (ii) a mock-up of the target satellite equipped with thrusters and Launch Adapter Ring (LAR). On the upgraded test-bed, the entire operation of capturing a rotating target object can be simulated. Such an operation includes the chaser approach phase, interception of the target object with the use of the gripper, and the post-capture phase. Only a few other microgravity simulators allow for such experiments to be carried out [9]. Results of experiments presented in this paper demonstrate the new capabilities of the test-bed and show that the air-bearing microgravity simulator at CBK PAN can be used for validation of various technologies required to conduct IOS and ADR missions.

The paper is organized as follows. An overview of the air-bearing test-bed is given in Section 2, while Section 3 contains a description of test-bed subsystems. The results of experiments conducted on the test-bed are shown in Section 4. The conclusions are given in Section 5.

2. AIR-BEARING TEST-BED OVERVIEW

The planar air-bearing microgravity simulator at CBK PAN is based on a 2 m x 3 m granite plate. The plate is supported by three adjustable legs that allow precise leveling of the surface. Due to the limited size of the granite plate, experiments have to be conducted with scaled-down models. All models are designed with the use of scaling laws [21]. As a result, their dynamic behaviour, taking into account the restriction of movement to one plane, corresponds to the dynamic behaviour of the full-scale objects.

Two mock-ups are used in experiments: one is the chaser satellite mock-up equipped with a manipulator, and the other is the newly added mock-up of the target satellite. Both mock-ups are equipped with on-board computers and cold-gas thrusters. Each mock-up is supported by air-bearings that allow frictionless motion on the surface of the granite plate. The external visual pose estimation system measures the position and orientation of the chaser satellite, the target satellite and the manipulator end-effector. This system consists of three industrial cameras (5 MPx resolution) placed above the test-bed's surface. All elements of the test-bed are shown in Fig. 1.

3. TEST-BED SUBSYSTEMS

3.1. Chaser satellite

The mock-up of the chaser satellite simulates a servicing satellite designed to intercept another satellite in order to carry out servicing tasks or to remove space debris from orbit. The currently used mock-up was constructed as part of the project “Development and validation of the laboratory model of a space robot equipped with resistojet thrusters,” funded by the NCBiR [14]. A schematic diagram of this mock-up is presented in Fig. 2.

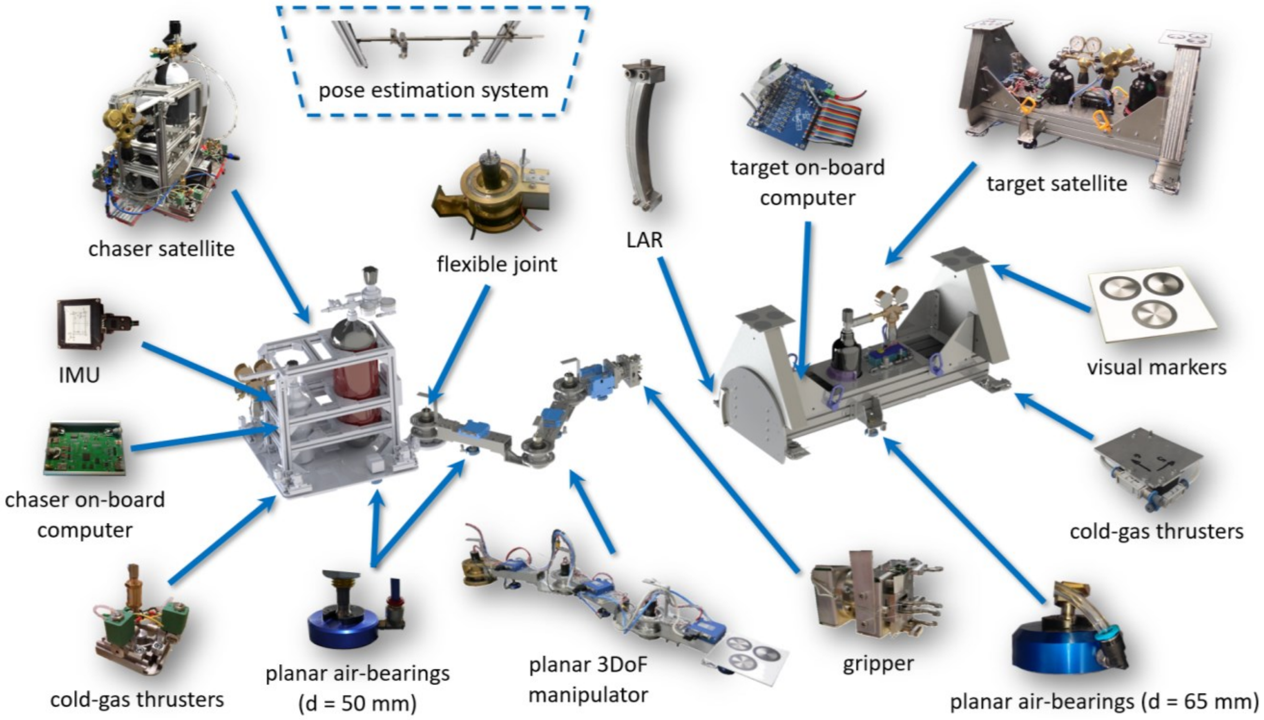

Figure 1. Elements of the planar air-bearing microgravity simulator at CBK PAN.

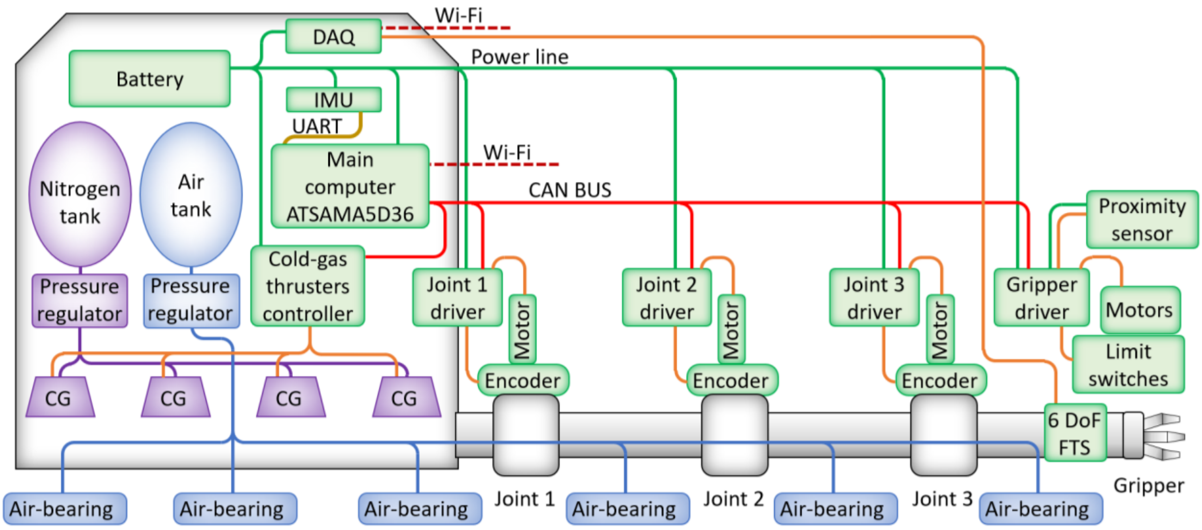

Figure 2. Schematic diagram of the satellite-manipulator system operated on the air-bearing test-bed.

The mock-up is based on a flat plate, on which a support truss is mounted. Three air-bearings are attached to the plate from below. Flat round air-bearings with a 50 mm diameter (model S105001 supplied by New Way Air Bearings) are used, operating at a pressure of 4.5 to 6 bar. Air is supplied to the bearings through flexible hoses connected to an air tank on the support truss. Cold-gas thrusters are used for optional control of the chaser satellite's position and orientation on the test-bed's surface. The mock-up is equipped with 8 thrusters grouped in four modules placed in the corners of the plate. These thrusters were developed by the Institute of Heat Engineering at Warsaw University of Technology [22]. Each of them can generate a nominal thrust of 0.846 N. Nitrogen stored in a tank attached to the support truss is used as a propellant gas for the cold-gas thrusters. The main on-board computer of the chaser satellite mock-up is based on ATSAMA5D36. CAN BUS protocol is employed for communication between the main computer, cold-gas thrusters controller, drivers of manipulator joints, and gripper driver. The mock-up of the chaser satellite is also equipped with an Inertial Measurement Unit (IMU) that provides precise measurements of the satellite's angular velocity and linear acceleration. The IMU is connected with the main computer through UART interface. The parameters of the chaser satellite mock-up are provided in Tab. 1.

Table 1. Parameters of the chaser satellite mock-up.

Parameter	**Value**
Mass	58.69 kg
Mass moment of inertia	$2.417\ \mathrm{kg} \cdot \mathrm{m}^2$
Position of the manipulator mounting point (wrt CoM)	$[0.377\ \mathrm{m} \quad -0.001\ \mathrm{m}]^T$
Size of the base plate	$0.5\ \mathrm{m}\ \times 0.5\ \mathrm{m}$

3.2. Manipulator

A 3-DoF planar manipulator is attached to the chaser satellite mock-up. This manipulator, initially with only two rotational joints, was designed and constructed as part of the project “Design and construction of the prototype space manipulator as a key element of the on-orbit servicing system” funded by the NCBiR [23], while the third rotational joint was added during the project “Mobility of a nonholonomic space robot constrained by large movable obstacles” funded by the Polish National Science Centre (NCN) [20].

Each joint of the manipulator consists of a DC motor, a harmonic drive, and an absolute optical encoder. Manipulator links are made from aluminium profiles. Each link is supported by one air-bearing (the same model of bearings is used as that used to support the chaser satellite mock-up). Resilient suspension plates in the joints allow compensation of possible vertical misalignments between links and ensure that all bearings are in exactly the same plane. The second and third manipulator joints are rigid, while the first joint can be either rigid or flexible, allowing for research on flexible-joint space manipulators [24]. In the case of tests with a flexible joint, it is possible to install an additional encoder to measure the angular position of the joint’s flexible part. The parameters of the manipulator are given in Tab. 2.

3.3. Modular Gripper

In planned ADR and IOS missions, it is commonly assumed that the capture operation will involve grabbing the LAR of the target satellite. To simulate this manoeuvre on the planar air-bearing microgravity simulator, a gripper, called the Launch Adapter Ring Modular Gripper (LAR-MG), was developed and added to the last link of the manipulator [25]. This gripper is based on an innovative kinematic solution. Three tentacle

Table 2. Parameters of the planar 3-DoF manipulator.

Parameter	**Link 1**	**Link 2**	**Link 3 + gripper**
Mass	2.81 kg	2.82 kg	4.64 kg
Mass moment of inertia	$0.0637\ \mathrm{kg \cdot m^2}$	$0.0635\ \mathrm{kg \cdot m^2}$	$0.0515\ \mathrm{kg \cdot m^2}$
Length	0.449 m	0.449 m	0.310 m
Position of CoM wrt joint *i*	$[0.136\ \mathrm{m} \quad -0.002\ \mathrm{m}]^T$	$[0.134\ \mathrm{m} \quad 0]^T$	$[0.151\ \mathrm{m} \quad 0]^T$

arms are used to grasp the LAR (the two external arms make contact with the inner surface of the ring, while the central arm touches the outer surface of the ring). Each tentacle arm, driven by a crank and erected by a spring force, grasps the edge of the ring and pulls it towards the hard-stop, where the ring is securely fixed using the crank's dead centre. Four DC motors with a high-ratio reduction gear are used as actuators. The gripper is also equipped with electromechanical limit switches. An inductive proximity sensor detects when the LAR is within the grasping range and initiates the closing of the gripper. A 6-DoF force/torque sensor (type 9306A31 produced by Kistler), mounted between the gripper and the last link of the manipulator, provides precise measurements of forces and torques during the grasping operation at 1 kHz frequency. The Modular Gripper allows for successful grasping of the LAR, even in the case of relatively high positioning errors. The design of the gripper is depicted in Fig. 3.

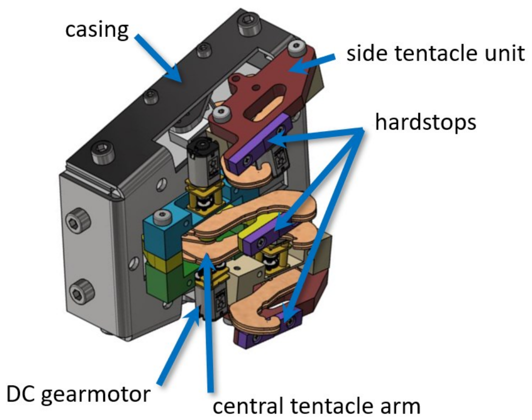

Figure 3. Design of the Modular Gripper.

3.4. Target satellite

The mock-up of the target satellite simulates a malfunctioned satellite or space debris to be captured during IOS or ADR mission. The construction of this mock-up is based on aluminium plates and system profiles. The mock-up is significantly larger and heavier than the mock-up of the chaser satellite. Furthermore, additional weight is added to achieve the necessary mass and inertia as dictated by the scaling laws. Model of a LAR fragment is attached to the mock-up as a grasping interface (LAR geometry is based on the LAR CASA CRSS 1194 SRF). The target satellite mock-up is supported by three air-bearings. Flat round air-bearings with a 65 mm diameter (model S106501 supplied by New Way Air Bearings) are used, operating at a pressure of 4.1 bar. Eight cold-gas thrusters are used for control of the satellite's position and orientation. These thrusters use compressed air as a propellant instead of nitrogen. There are two separate air-tanks stored on-board of the mock-up: one supplies compressed air to the air-bearings, while the other supplies compressed air to the cold-gas thrusters. The main on-board computer of the target satellite mock-up is based on Raspberry Pi. The design and the schematic diagram of the target satellite mock-up are shown in Fig. 4 and Fig. 5, respectively. The parameters of this mock-up are provided in Tab. 3.

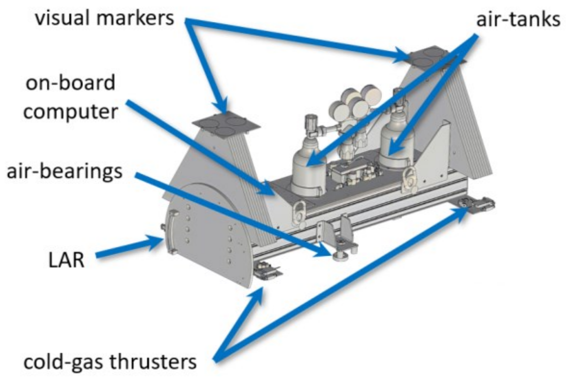

Figure 4. Design of the target satellite mock-up.

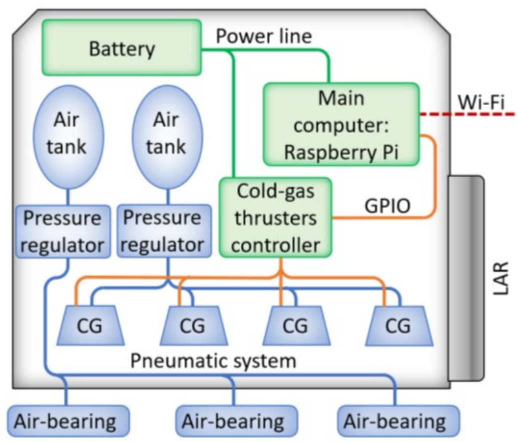

Figure 5. Schematic diagram of the target satellite mock-up.

Table 3. Parameters of the target satellite mock-up.

Parameter	Value
Mass	153.5 kg
Mass moment of inertia	$29.87\ \mathrm{kg} \cdot \mathrm{m}^2$
Position of the LAR grasping point (wrt CoM)	$[0.534\ \mathrm{m} \quad -0.166\ \mathrm{m}]^T$
Size of the base plate	$1.037\ \mathrm{m}\ \times 0.526\ \mathrm{m}$

4. RESULTS OF EXPERIMENTS

4.1. Validation of new elements of the test-bed

The new elements of the test-bed have been thoroughly tested to verify their correct operation and to confirm that they meet all design requirements. During preliminary tests, gains of controllers responsible for the control of the target satellite mock-up's cold-gas thrusters were tuned. To allow simulation of the entire capture operation the target mock-up must rotate with the desired angular velocity. Fig. 6 presents the angular velocity of the mock-up measured during one of the qualification tests. The control system used cold-gas thrusters to accelerate the mock-up to the desired angular velocity and keep constant position of the mock-up's Centre of Mass (CoM). The capture operation can begin once the mock-up has reached the desired velocity. Duty cycle of thrusters during this experiment is shown in Fig. 7. A separate test campaign was conducted to experimentally determine the gripper's capture envelope and evaluate its performance. Results of the gripper tests are summarized in [25].

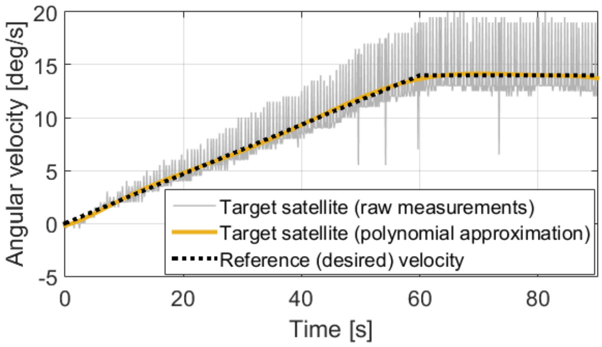

Figure 6. Agnular velocity of the target satellite mock-up during qualification test.

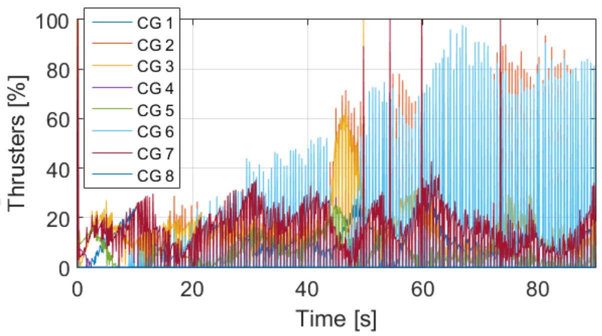

Figure 7. Duty cycle of target's cold-gas thrusters.

4.2. Tracking optimal collision-free trajectories

A very large group of experiments conducted on the planar air-bearing microgravity simulator at CBK PAN is related to the validation of trajectory planning and control algorithms for a free-floating space manipulator. In these experiments we assume that control of the chaser satellite's position and orientation is switched off in the final phase of the capture manoeuvre. As a result, the momentum and angular momentum of the satellite-manipulator system is conserved before the first contact with the target object. In this section we present results of experiments that demonstrate an optimal trajectory planning using spline-based trajectories. The trajectory planning algorithm is presented in [17], where its validation based on the results of numerical simulations and experiments is also shown. The algorithm generates a collision-free trajectory of the manipulator that results in the desired position and orientation of the end-effector and the desired orientation of the chaser satellite.

The end-effector trajectory on the XY plane and the end-effector orientation are presented in Fig. 8 and Fig. 9, respectively, while the orientation of the chaser satellite is presented in Fig. 10. Frames from a camera used by the pose estimation system are shown in Fig. 11. It can be seen that the manipulator avoided collision with a rectangular obstacle, while the end-effector reached the desired position and orientation. In the considered case the changes in the satellite's orientation are solely caused by the manipulator's motion. The manipulator trajectory was optimized to achieve the desired orientation of the chaser satellite. The orientation obtained at the end of the experiment closely matches the desired value. Thus, the trajectory planning algorithm worked correctly. In addition, the experiment showed that the disturbances acting on the satellite-manipulator system on the test-bed are relatively small and that the parameters of the system are known with high accuracy. Fig. 8, Fig. 9, and Fig. 10 show results of a single test selected from a test campaign presented in [17].

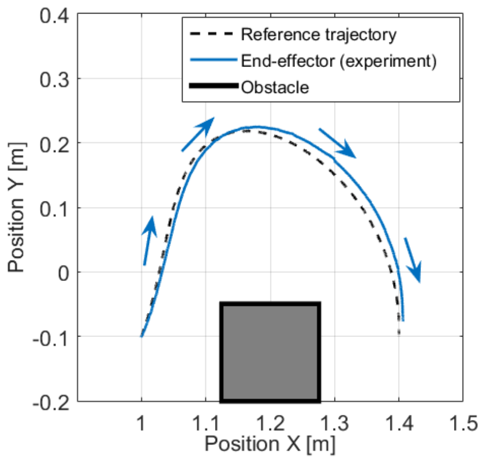

Figure 8. Optimal collision-free end-effector trajectory on the XY plane.

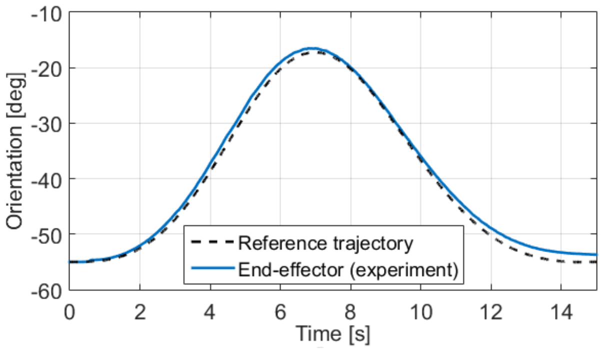

Figure 9. Optimal trajectory: end-effector orientation.

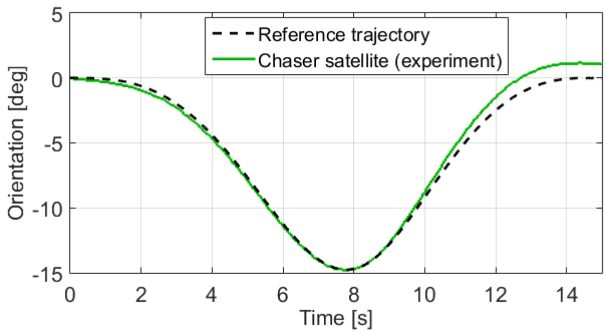

Figure 10. Optimal trajectory: orientation of the chaser.

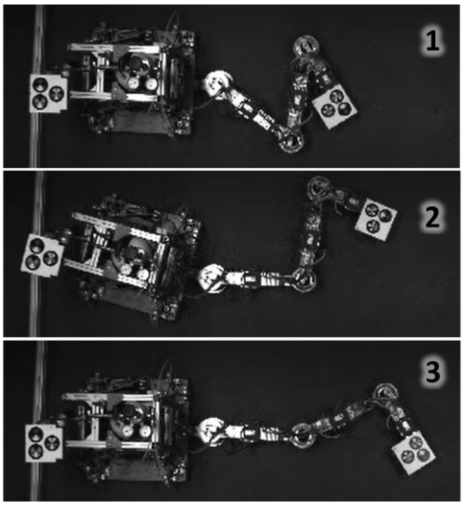

Figure 11. Optimal trajectory: frames from a camera used by the pose estimation system [17].

4.3. Capture operation

Following the addition of the Modular Gripper and the target satellite mock-up, the air-bearing test-bed at CBK PAN can be used to simulate the entire capture operation. Exemplary results of the critical part of this operation are presented in this section to demonstrate the extended capabilities of the test-bed. In the selected scenario the target satellite was rotating with the angular velocity of 3 deg/s at the moment of grasping. The end-effector followed a pre-planned trajectory and approached the LAR in a straight line with respect to the target satellite to avoid collisions. Control system based on the Dynamic Jacobian was used to ensure accurate end-effector trajectory tracking. The position of the end-effector and the LAR, obtained from the external pose estimation system, are presented in Fig. 12 (X-axis) and Fig. 13 (Y-axis). Fig. 14 shows the orientation of the end-effector and the LAR. The vertical line in Fig. 12, Fig. 13, and Fig. 14 marks the moment when the gripper started closing. The test set-up during one of the conducted experiments is shown in Fig. 15, while Fig. 16 presents frames from an additional camera mounted on the target satellite. The obtained results show that the manipulator control system was able to ensure accurate trajectory tracking. The final end-effector positioning error was within the misalignment tolerance of the gripper. In all conducted experiments, the Modular Gripper successfully grasped the LAR of the rotating target satellite. The experiments also demonstrated the correct operation and effectiveness of the newly designed gripper.

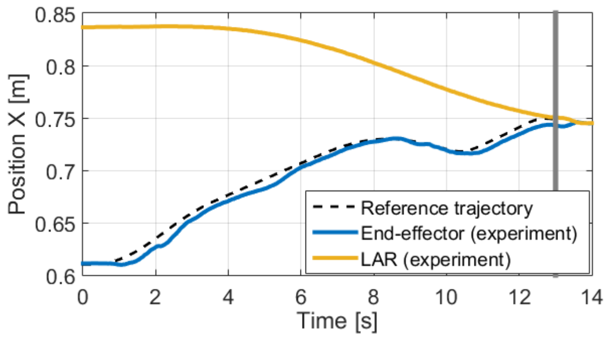

Figure 12. Capture operation: position of the end-effector and the LAR on the X axis.

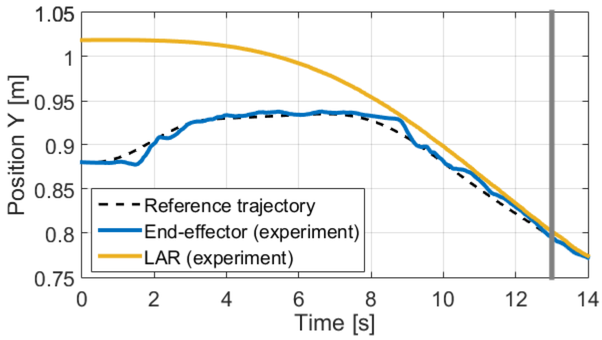

Figure 13. Capture operation: position of the end-effector and the LAR on the Y axis.

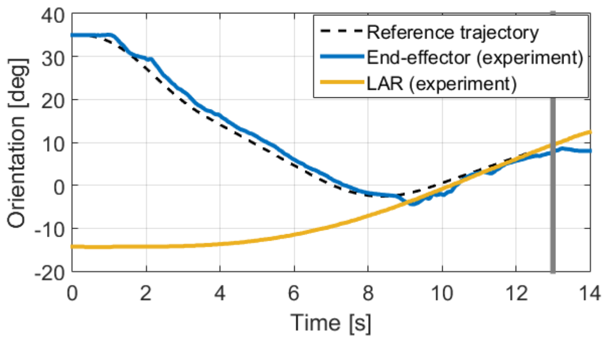

Figure 14. Capture operation: Orientation of the end-effector and the LAR.

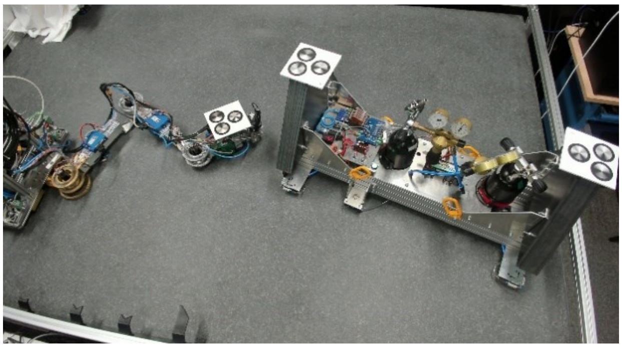

Figure 15. Photo of the manipulator and the target satellite mock-up taken during the capture operation.

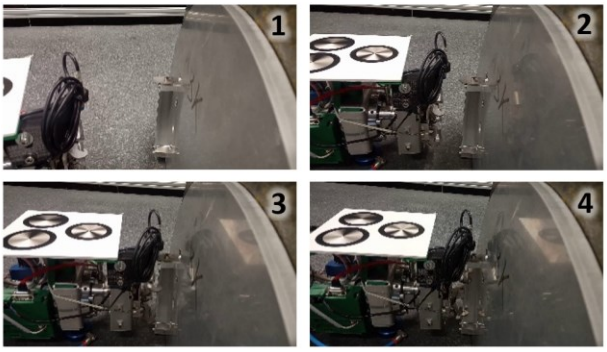

Figure 16. Frames from a camera mounted on the target satellite showing the grasping of the LAR.

5. CONCLUSIONS

Testing facilities that allow the simulation of microgravity conditions play a crucial role in validation of technologies developed for IOS and ADR missions. Over twelve years of continuous operation, the planar air-bearing microgravity simulator at CBK PAN has proven its reliability, versatility, and potential to obtain high-quality results. Several major upgrades of the test-bed expanded its capabilities and opened up new fields of research. Two new elements were added to the test-bed in the most recent upgrade: the Modular Gripper and the mock-up of the target satellite. These elements were thoroughly tested and it was confirmed that they meet all requirements. With the Modular Gripper and the target satellite mock-up, it is possible to simulate the entire operation of capturing a rotating target object. This allows to perform experimental verification of trajectory planning and control algorithms dedicated for the in-orbit capture operation. A 6-DoF force/torque sensor allows to test compliant control algorithms that are crucial for the grasping phase. Validation of hardware components of robotic systems could also be conducted.

Results presented in this paper show that the newly introduced target mock-up can accurately reproduce the desired rotational motion of object such as uncontrolled space debris. The experiment, in which the end-effector followed the optimal collision-free trajectory, showed the potential to use the test-bed for validating innovative algorithms and conducting scientific research. The fact that the changes in the chaser's orientation measured during the experiment are very close to the predicted changes obtained from numerical simulation indicates that the disturbances are very small and the parameters of the satellite-manipulator system are known with high accuracy. The test-bed very precisely emulates the dynamics of the free-floating satellite-manipulator system. Finally, the results of the capture experiment demonstrate that it is possible to conduct simulations of complex manoeuvres. Successful grasping of rotating target object requires proper operation of the control system and various hardware components. Only a few such experiments have been conducted on other test facilities.

Work is currently underway to perform experimental validation of selected components of the TITAN manipulator that is being developed in the frame of the project “Robotic Arm Development for On-Orbit Servicing Operations” funded by ESA. It is also planned to add a reaction wheel for precise control of the chaser satellite’s orientation.

6. ACKNOWLEDGMENTS

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