Application of Impedance Control in Robotic Manipulators for Spacecraft On-orbit Servicing

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***Abstract*— On-orbit satellite servicing is a technology that is expected to transform the space sector in the coming years. Space robotics is a promising approach to refuel, repair, update, and transport satellites on orbit. However, safe and reliable docking with the client satellite, needed as part of most servicing operations, is still considered a challenge. This paper presents an autonomous robot-based approach for this purpose. An impedance control strategy is added to the controller of a conventional robotic manipulator to allow compliant and safe manipulation of a spacecraft docking mechanism. This setup is expected to facilitate autonomous docking and manipulation operations with cooperative and non-cooperative on–orbit serviced satellites. Platform-art$^{©}$, a dynamic test bench for hardware-in-the-loop validation of space GNC technologies is used to test the proposed approach.**

Keywords—impedance control, robot, manipulator, on-orbit servicing

I. INTRODUCTION

The extension of life time of satellites through on-orbit servicing is one of the main objectives of the space agencies and industry in the last years. The extension of the service lifetime of a healthy satellite would have a direct impact in the profitability of satellite operators and in the price per bit of the services provided to their clients. Refuelling of on-orbit satellites is one of the key technologies for satellite lifetime extension, since propellant depletion is one of the main causes of satellite decommissioning. In order to perform refuelling operations it is mandatory to achieve a hard docking/berthing, implying a pressurized connection for fuel transfer and possibly a rigid mechanical coupling and physical data link. Other on-orbit lifetime extension servicing operations, such as tug (towing) services, could impose different requirements on physical connection between spacecraft, such as not needing a pressurized connection or a data link. However, a hard mechanical coupling between spacecraft is required in most of on-orbit services, and this implies the need for a docking/berthing manoeuvre.

Docking is the process of joining two separate flying free spacecraft, while in berthing the active spacecraft uses a robotic arm to place an inactive spacecraft into a mating interface. Although docking does not necessarily imply the use of a robotic arm, the robot-based approach is considered promising since a robotic arm a) provides extended work volume in which docking process can be completed, and b) allows fine and flexible control of the forces exerted on the client spacecraft.

However, there are still challenges that need to be addressed before robot-based approach is fully applied to on-orbit servicing, among them:

- The risk of impact between the end-effector and the serviced spacecraft, implying high contact forces in the manipulator [1] that can result in separation of the two spacecraft.
- The definition of a control strategy that maximizes the probability of successful docking, even in presence of relative, not-modelled motion between spacecraft.

The use of impedance controllers has been proposed in previous works to tackle the first challenge. For example, an impedance controller is proposed in [2] to grasp a tumbling target. In addition, it has been proven that this kind of control also works without the need of sensor data (force feedback), using a disturbance observer, also in space grasping [3]. When robotic system has more than one arm an IC variation exists called multiple impedance control (MIC), which was also proven to grasp [4]. In [5] an analytical and experimental approach is proposed for assessing the use of an impedance-controlled manipulator for on-orbit docking manoeuvres.

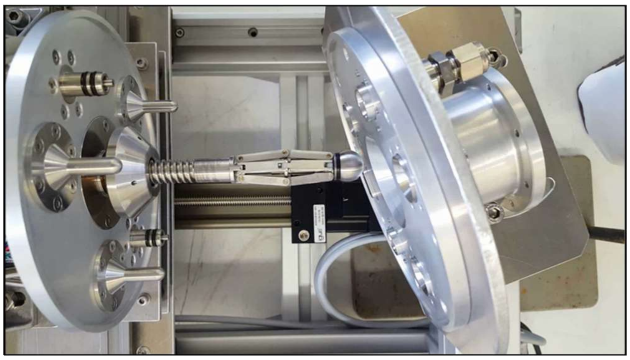

Fig. 1. ASSIST breadboard, photo ESA courtesy. The docking fixture is shown in the right part, and the docking end effector in the left part.

There are also plenty of applications where impedance controllers can be used outside the space sector. For example, they can be used in industry for high accuracy tasks in environments with some level of compliance to avoid force overshoots that would result in task failures [6]. Force limits can be applied to an impedance controller to use them as constraints in the control action [7], this allows a gentle manipulation for environments with fragile components.

Several designs of docking/berthing devices have been proposed in the last years specifically for on-orbiting servicing purposes, such as the International Docking and Berthing Mechanism [8]. Another example of these docking mechanisms is the ASSIST device [9]. The ASSIST has been specifically designed for spacecraft servicing, and allows transfer of fuel and data while providing mechanical linkage between spacecraft. This device includes two main elements:

1) The docking fixture, the mechanical interface on the serviced spacecraft. It is equipped with a drogue cavity providing mechanical interface with the end-effector probe.

2) The end-effector, the mechanical interface on the servicing spacecraft installed on a robotic arm. The end effector is equipped with a probe designed to be introduced into the drogue cavity of the docking fixture. Once introduced, the probe expands preventing the probe from going out of the drogue, resulting in a soft docking of the two ASSIST parts. In the next phase, a centring cone located at the base of the probe is displaced towards the docking fixture, resulting in partial alignment of the two ASSIST elements. Finally, the fluid plane of the end effector is displaced also towards the docking fixture, resulting in a hard docking. At this point the two halves are rigidly connected and data and fluid transfer can be enabled.

Several kinds of experimental test platforms can be used to simulate berthing/docking manoeuvres in space, being the most common ones air-bearing tables and robotic hardware-in-the-loop (HIL) systems.

Air-bearing tables allow spacecraft engineering models moving freely on a plane making use of air cushions that greatly reduce friction between the model and the table, allowing motion in three degrees of freedom (two translational and one rotational).

HIL robotic test benches make use of robotic manipulators and related controllers to simulate the dynamic behaviour of the spacecraft, through the recreation of relative trajectory and attitude profiles, which can be generated in real time and in closed loop from sensor data. The sensors installed on top of the robot's end-effectors, experience the same relative kinematics and produce the same measurements as in space environment, including most of the significant space effects, such as in-orbit realistic illumination and perturbations. In case of manoeuvres involving contact between spacecraft (e.g. docking), force measurement on end-effectors allow simulating the dynamic behaviour of the two free-floating spacecraft. The main advantage of HIL robotic test benches is that they allow six-dimensional motion of the simulated spacecraft (three translational and three rotational degrees of freedom), compared with the three-dimensional motion simulated by air-bearing table setups. In addition, robotic test benches generally allow testing heavier engineering models.

An example of HIL robotic setups is platform-art© [10], GMV's test bench for supporting and enhancing the validation of space GNC technologies and related metrology equipment, with real air-to-air metrology dynamic stimulation, real-time and closed loop testing capability. This test bench is used for on-ground, validation of space GNC systems and sensors equipment for several scenarios as Formation Flying, Rendezvous & Docking, Landing, and Robotic applications.

This work focuses on the implementation and testing of control strategies for a robot-based docking system oriented to on-orbit servicing. The objective of the controller is to allow completing the capturing phase (in which the two spacecraft are in contact) safely and effectively. Several control strategies are proposed to facilitate a successful docking for different initial conditions (relative speeds of spacecraft), and they are validated using platform-art© HIL robotic test bench. A simplified model of the ASSIST device is used in these tests as example of a realistic docking device for on-orbit servicing and to facilitate the comparison of results with other works.

This paper is structured as follows: Section II describes the Impedance control approach proposed to allow for compliant manipulation of the docking device, and the implementation of this approach in the commercial manipulator used for testing. Section III presents different manipulator control strategies, based on the impedance controller presented before. These strategies are designed for completing a docking manoeuvre with a moving target using only the sensor feedback provided by a force/torque sensor installed on the manipulator. Section IV presents the use case considered for evaluation and the results obtained when testing the impedance controller and the different control strategies in a HIL test bench simulating different conditions, such as different linear and rotational relative spacecraft speeds. Finally, Section V presents the conclusions of the work and proposes different lines for future activities.

II. IMPEDANCE CONTROL FOR COMPLIANT MANIPULATION OF DOCKING DEVICES

A. Impedance Control

Impedance control (IC) for robot manipulation was initially suggested by Neville Hogan [11]. Manipulation requires a supervised and controlled mechanical interaction. For this purpose, IC method regulates the relationship between robot movement and exerted force, increasing robot adaptability to interact with its environment. This relationship is obtained by variables and parameters from a Single Degree of Freedom (SDOF) equivalent system, whose basic equation is:

$$f = m\Delta\ddot{x} + b\Delta\dot{x} + k\Delta x, \qquad (1)$$

where m, b and k are respectively the mass, damping and stiffness of the SDOF system, f is the force and Δx is the displacement. In a robotic application, displacement is the dependent variable whereas force is the controlled one. Therefore, the main objective is to obtain displacement.

$$\Delta\ddot{x} = \frac{f - b\Delta\dot{x} - k\Delta x}{m} \qquad (2)$$

Once $\Delta\ddot{x}$ is known (2), $\Delta\dot{x}$ can be determined by integration:

$$\Delta\dot{x} = \int \Delta\,\ddot{x} \cdot dt \qquad (3)$$

In the end, displacement is calculated integrating once more:

$$\Delta x = \int \Delta\,\dot{x} \cdot dt \qquad (4)$$

Altering robot trajectory according to this displacement, the robot can interact with its environment as a SDOF system. Impedance parameters will describe how this interaction will be. Interaction dynamics can be analysed through the impedance ratio on Laplace space:

$$Z(s) = \frac{F(s)}{x(s)} = ms^2 + bs + k \qquad (5)$$

For an input displacement mass and damping determine how force transitional behaviour is, while force on steady state is proportional to stiffness and displacement.

Within force control strategies, impedance is particularly feasible for applications in which there is no specific model for interaction. This strategy just needs stable parameters, which will define how much force is exerted on target and how fast is the settlement.

B. Implementation of IC in a conventional robotic manipulator

A library was designed to compute IC regardless other runtime operations from robot. This library has some public functions which enables user to run IC and set up its parameters and runtime period. Wider explanations of these functions are listed below:

- ***setParams***: set stiffness, damping and mass for each DOF.
- ***setExecutionPeriod***: set period in which impedance will be executed. Ensuring this period is firmly necessary to compute IC properly.
- ***enableDisableAxis***: let user to enable or disable IC in each DOF.
- ***getJointVariation***: uses joint setpoint calculated by trajectory controller and force measured on Tool Centre Point (TCP). This function computes the joint position increments needed to move robot according to IC.

Executing *getJointVariation* deterministically and adding its result to the setpoint obtained by the path planning function, the robot will react to forces measured in TCP. Different control strategies can be followed for defining the setpoint as explained in Section III, resulting in different behaviour of the manipulator.

This library is a simple solution to integrate IC in a robotic manipulator without modifying other robot mechanisms (such as trajectory planner). Nevertheless, it requires internally a robot model with link dimensions and joint types. This model can be easily modified by the developer in order to consider a different robot.

III. MANIPULATOR CONTROL STRATEGIES AND CONFIGURATIONS FOR DOCKING

Several strategies and configurations to control the motion of the end-effector are proposed in this section with the aim of introducing the probe in the drogue cavity, allowing for the completion of the docking procedure. Note that a perfect match between end effector and target docking fixture is not needed, since the active end-effector is designed to complete a hard docking by mechanical means once the probe is inserted in the drogue cavity for enough time. The control strategies and configurations proposed and tested focus mainly on: a) the definition of the setpoint to follow in the impedance control and b) the definition of the force application point in different positions within the probe. Different sets of control parameters are adjusted for the possible combinations of a) and b) configurations so the reaction becomes more stiff or flexible. These control strategies and configurations are described in the following subsections.

A. Impedance control setpoint variations

a) Pure Impedance control

This control strategy makes use of the impedance control as described in Section II. The TCP of the manipulator is commanded to move at constant linear speed, in the direction defined by the axis of the end-effector. Then, if the end effector rotates due to the forces applied on it, the trajectory followed by the end effector will turn accordingly. This change in the pose of the end-effector is expected to allow for proper insertion of the probe, even in the case that the target docking fixture is rotating.

b) Hybrid Impedance Control

In this case, the setpoint is not varied in time to follow a desired trajectory; instead, the displacement obtained in Eq. 4 is added to current robot position and to the desired displacement along the end-effector axis, and the result is the new robot setpoint for next iteration.

Now the meaning of the displacement changes, as it is the arm deviation respect to the setpoint in just one loop, not with respect to a trajectory. In this case, the stiffness of the controller must be much larger, compared with case a), to avoid instability. Execution time also determines how fast displacement is accumulated on the setpoint, being a fundamental factor in the stability of the robot movement.

The first strategy is suited for tasks where the impedance control is based on a precomputed trajectory, the second one is more suitable for cases where there is not a defined path for the robot to follow. In the case of docking, the first strategy would be suitable for the approach phase and the second one could be used once the probe has been inserted in the drogue.

In the tests described in section IV it is assumed that the approach phase has been already performed before the start and the probe is about to be inserted in the drogue, so the second approach was chosen.

B. Force application point variations

The intuitive point to read the forces and apply the impedance control is the load cell itself, but as it can be seen in Fig. 2, using this point can lead to the probe exiting the drogue. If this point is displaced to the probe tip or even further, the arm movement increases, but tends to keep the probe inside the drogue and to rotate it towards the correct orientation.

Changing the application point means that the force measurement has to be transformed to provide the impedance control with the force that a virtual load cell would read in that position. After this transformation, the linear forces remain unchanged, but the torques change as the distance to the force point changes. In this case, the application point is always placed along the end-effector probe axis, which is aligned with the load cell. Then, the change in distance does not affect the torque around the end-effector axis. The variation in the remaining two components is computed as follows:

$$\mathrm{T_x} = \mathrm{F_x d}; \qquad (6)$$

$$\mathrm{T'_x} = \mathrm{F_x d'} = \mathrm{F_x (d - D)} = \mathrm{T_x} - \mathrm{F_x D}; \qquad (7)$$

being *d* the distance between the force and load cell, *d'* the distance from the force to the application point and *D* the distance between those two points (see Fig. 3).

Depending on the control parameters, this change can lead to increased forces applied to the drogue. For this reason, the control in the linear axes has to be flexible enough, so that the end-effector does not exceed the desired forces even if it rotates towards the drogue.

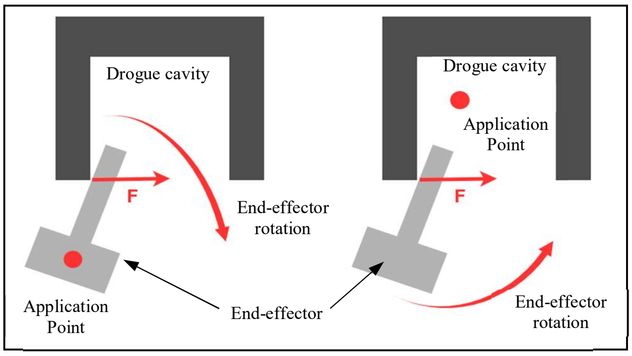

Fig. 2. Different arm reactions varying the force application point (red dot).

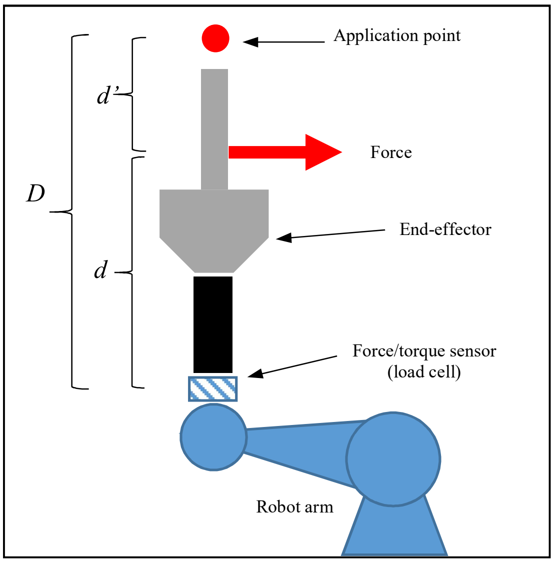

Fig. 3. Definition of Application Point and distances *d*, *d'* and *D*.

The ideal application point is the one receiving the lateral forces from the drogue when there is no misalignment. As this point is almost impossible to compute for most applications, the application point can be selected empirically based on the observed end effector rotations with respect to the received forces.

IV. EXPERIMENTAL EVALUATION

A. Use case description

A mock-up of a docking end-effector and docking fixture are employed for the experimental evaluation presented here. This mock-up has been designed to roughly resemble the main dimensions and characteristics of the ASSIST device [7]. Note that only the probe, centring cone, alignment pins, fluid couplings and fluid plane are emulated. Observe also that this mock-up is completely passive while the ASSIST end-effector includes active mechanisms. Finally, it must be considered that the mock-up is rigid and does not include any mechanical compliance device (spring).

The proposed control approach has been tested in platform-art© introduced in section I. Platform-art© is composed, among other systems, of two industrial manipulators, one of them mounted on a linear servo-controlled track. These manipulators are used to simulate the dynamic behaviour of the target and chaser spacecraft, and can hold engineering models of the spacecraft (mock-ups), sensors (cameras, load cells), or other mechanical devices (docking or grasping mechanisms, etc.). The test bench includes all related control system allowing for coordinated control and simulation of spacecraft motion. Additionally, a commercial small manipulator is used to manipulate the docking end-effector mock-up and it implements the impedance controller.

The experimental setup is described next:

- A mock-up of a docking end-effector, described above in this section is mounted on the docking manipulator.

- The docking manipulator is equipped with a 6-dof force/torque sensor installed between the end-effector and the manipulator wrist. The manipulator controller implements the impedance control described in section II.
- The docking manipulator base is mounted on the wrist of the chaser manipulator of platform-art©.
- The docking fixture, is mounted in the platform-art© target manipulator.

Note that in this setup, the spacecraft simulated by the platform-art© manipulators are assumed to have enough mass so the effects of the manipulator motion and the contact forces in the docking fixtures do not affect their initial trajectories. In other words, platform-art simulates the behaviour of two spacecraft with such a mass/inertia that the variations caused in the trajectory of the spacecraft are negligible. This is acceptable in the first stages of testing, but in future tests it is planned to use force feedback to simulate the behaviour of free floating spacecraft.

In the initial state, the two platform-art© manipulators are positioned so that the docking fixture is centred in the workspace of the docking manipulator. The docking manipulator is positioned so that the end-effector probe tip is located within the acceptance cone of the docking fixture, ready to start the insertion of the probe.

The test cases are defined as a combination of the following cases:

- The force application point (Application Point) is in the load cell (case tagged *sensor in* Table I) or 10 cm past the end-effector probe tip (case tagged *fwd in* Table I).
- The spacecraft simulated by the platform-art© manipulators have different combinations of linear (m/s) and angular (rad/s) velocities relative to each other.

The values of the different magnitudes that define the test cases, which are representative of the working conditions that can be found in a real application, are depicted in Table I.

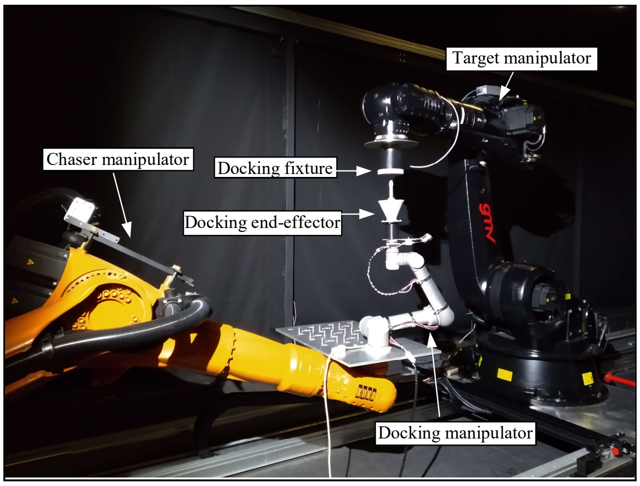

Fig. 4. Experimental setup in platform-art©.

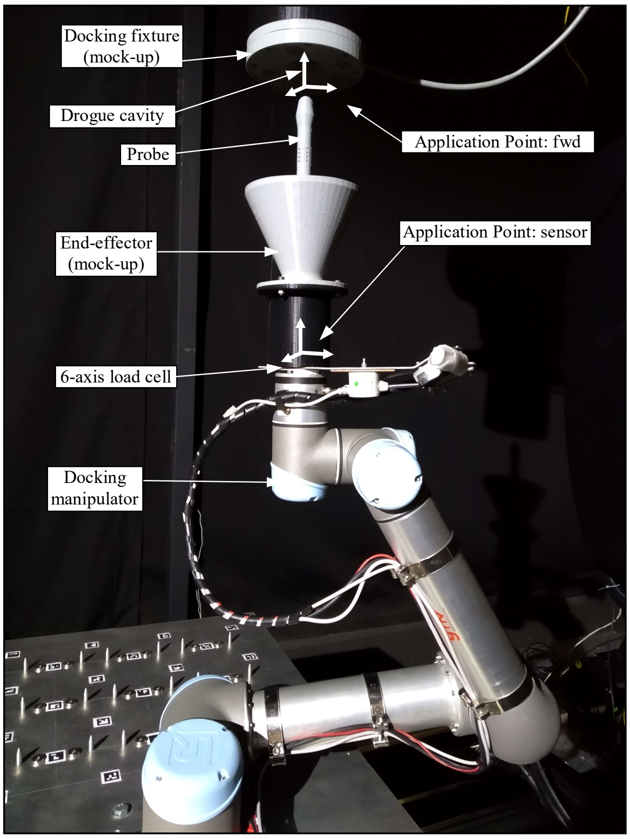

Fig. 5. Docking manipulator, docking end-effector and docking fixture.

After setting the initial conditions, the berthing manipulator is commanded to introduce the probe into the drogue following the approach described in section II.

B. Results

The first preliminary tests indicated that the use of a pure impedance controller (see section III-Aa) was not adequate in this experimental setup, in which a preferred trajectory is not defined. The forces exerted by the manipulator increase as the relative motion of the spacecraft displaces the end-effector, and this hampers the insertion of the probe. Instead, the hybrid approach proposed in section III-Ab seems to fit better this case. When the hybrid controller (see section III-Ab) is used, the docking manipulator is able to follow the docking fixture in a stable manner and with much lower interaction forces until docking is completed.

The following magnitudes are measured during the experiments to evaluate the performance of the hybrid controller:

- Task completion (TC), indicates if the probe is correctly inserted in the drogue, which would allow for correct latching of the end-effector mechanism.
- Successful alignment (SA), indicates if the end effector is able to follow the motion of the docking fixture, both in position and orientation during the whole test.

TABLE I. TEST RESULTS

Test case definition			***Test Results***	
Application Point	***Linear Relative Speed (m/s)***	***Angular Relative Speed (deg/s)***	***TC***	***SA***
Sensor	0	0	Yes	Yes
Sensor	0.01	0	Yes	No
Sensor	0	0.5	Yes	No
Sensor	0.01	0.5	Yes	Yes
Sensor	0.01	-0.5	Yes	No
Fwd	0	0	Yes	Yes
Fwd	0.01	0	Yes	Yes
Fwd	0	0.5	Yes	Yes
Fwd	0.01	0.5	Yes	Yes
Fwd	0.01	-0.5	Yes	No

Table I gathers the main results obtained with the hybrid controller for each of the defined test cases.

Note that in all cases the probe enters the drogue cavity allowing the latching of the end effector, and resulting in a soft docking. Nevertheless, the results indicate that selecting the force sensor (installed in manipulator wrist) as application point is not the best option. In this case, the forces exerted by the docking fixture on the end-effector result in a rotation that tends to expulse the probe from the drogue cavity. However, when the Application Point is placed in a forward position, the probe tends to stay in the drogue cavity in more cases and for more time, and the end-effector tends to remain aligned with the docking fixture (see Figure 6). This is considered highly beneficial in order to complete the hard docking process with minimal interaction forces.

Figure 7 shows the forces exerted by the manipulator on the docking fixture when the Application Point is set at the force sensor installed on the manipulator wrist (case *sensor*) and on an advanced position (*fwd* case). These graphics show that the forces exerted in the *fwd* case are considerably smaller. These graphs also show periodic peaks in the force, caused by the probe hitting the drogue cavity. For example, this phenomena causes the increasing peaks between seconds 40 and 45 in the *fwd* case. Note that the controller needs to be tuned carefully and the control loop frequency must be high enough to avoid over-reactions. When the probe is partially inserted in the drogue cavity, and touching one side of the cavity, an overreaction to the contact force can cause the probe to impact the opposite side of the cavity, resulting in an unstable motion. Since the difference of diameters of the cavity and the probe is small (approximately 2 cm) a control loop frequency of at least 100 Hz was needed to avoid this effect.

V. CONCLUSIONS

An impedance controller and several control strategies are proposed in this paper to regulate the motion of a robot-based spacecraft docking system. The results obtained in experimental evaluation show that the proposed hybrid controller approach is effective and allows completing the insertion of the docking end-effector probe in the docking fixture even if spacecraft are moving relative to each other or if the docking mechanisms are not aligned.

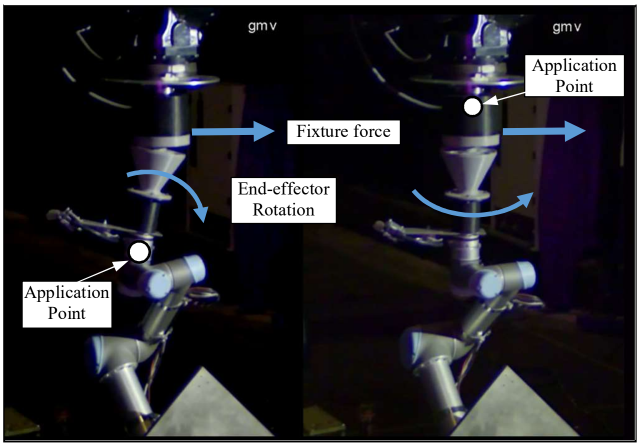

Fig. 6. Behaviour of the controller with the Application Point in the force sensor (left) and in a forward position (right)

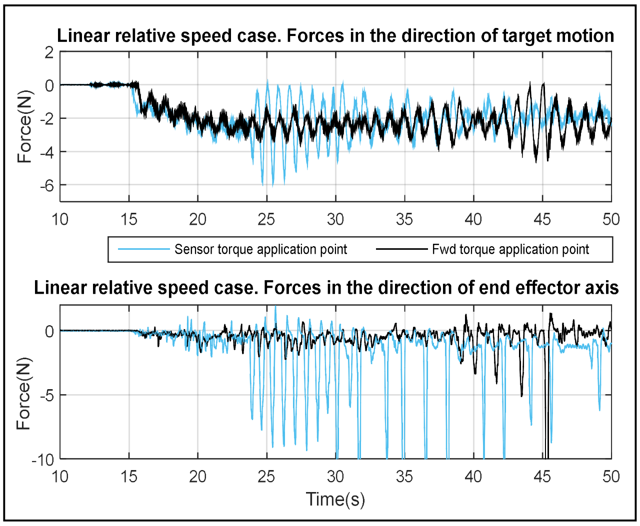

Fig. 7. Forces measured by the manipulator force/torque sensor.

In addition, two different configurations for the force Application Point are proposed to compute torques exerted on the end-effector. The results show that setting the Application Point in a forwarded position (near the tip of the probe or even further) is highly effective to keep the correct alignment between docking end-effector and docking fixture, and to increase the time the probe remains in the drogue cavity, despite of relative motion of the spacecraft.

The next expected steps continuing this work include the simulation of the dynamic behaviour of the chaser and target spacecraft floating free in the space by means of the platform-art© testbench. This will allow assessing the proposed approach in more realistic conditions. Future experiments will also include the testing of a prototype of an active docking end-effector fixture able to perform soft-docking and hard docking, after the probe has entered the drogue. The effect of these two manoeuvres on the two floating spacecraft and on the docking arm will be investigated to validate the impedance controller and control strategies proposed here in later docking phases and during demating as well. In addition, a controller based on visual servoing techniques will be implemented and tested using this experimental setup to test the complete docking process, including the spacecraft approximation phase.

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