THE SATLEASH EXPERIMENT: A STEP FORWARD IN TECHNOLOGY DEVELOPMENT FOR FUTURE ACTIVE DEBRIS REMOVAL MISSIONS

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ABSTRACT

The space community is nowadays well aware of the risks connected to space debris. For this reason, the research on this topic is very active and purposeful. In the last decade, the Department of Aerospace Science and Technology of Politecnico di Milano put a lot of effort in developing a clear strategy for Active Debris Removal, trying to increase the Technology Readiness Level of the proposed solution as much as possible. This paper wants to quickly recall the milestones reached by the Politecnico di Milano in the development of a net-based active debris capture strategy. Particular attention and emphasis will be reserved for the SatLeash experiment.

Key words: Active Debris Removal; Tether; Net; Space Tug.

1. INTRODUCTION

The approach that has been followed implies a net-based capture of the debris. This solution is preferable mainly because is safer than a contact-based mechanism and applicable to a wider class of debris. In fact, a net-tether capture allows a larger capture distance between the chaser spacecraft and the debris. On the contrary, the high flexibility of the net-tether systems implies a more complex control. Critical oscillations and vibrations can occur and must be damped and avoided. The road-map at Politecnico started with the development of a multi-body simulator able to reproduce the net deployment, contact and closure dynamics on the debris. Moreover, it is also able to simulate the flexible dynamics of the connecting tether. The net deployment, contact and closure simulation was previously validated with the PATENDER experiment on a parabolic flight part of an ESA contract. The SatLeash experiment has been the natural step forward in the validation and test of the proposed capture strategy. The Satleash experiment, part of the ESA Fly Your thesis program, was aimed at validating the tether dynamical model and, mostly, to test the tether control law. A reduced-scale tethered floating test bed, has been developed for the parabolic flight campaign. The design of the experiment includes a main rack, a secondary rack with a docking station and a floating module. A linear actuator was installed on the main rack. The actuator ideally reproduces the linear motion of the chase, controlled by the designed control law. The linear actuator is connected to the floating object through an elastic tether. As already said, the intrinsic flexibility of such kind of structures, zero gravity environment and coupled end-bodies dynamics lead to complex oscillation and vibrations. These instabilities phenomena have to be actively controlled and damped by the chaser spacecraft. A wave-based control, using tension feedback, was selected as control law to stabilize the system during tensioning and release phases. This paper wants to quickly recall the milestones reached by the Politecnico di Milano in the development of a net-based active debris capture and removal strategy. Particular attention and emphasis will be reserved for the SatLeash experiment. The promising results of the wave-based control in terms of vibration damping and robustness will be presented together with the validation of the dynamical model. Finally, a quick overview of the next steps will be presented.

2. PATENDER EXPERIMENT

The PATENDER experiment flown in June 2015 and its goal was to reconstruct the 3D motion of a net capturing a satellite mock-up to validate the dynamics numerical model. The net, stored in a canister, was deployed by shooting the bullets hanged on the net corners (see Fig.1) High-speed high-resolution cameras were used to track the flexible system dynamics evolution. The results of the 3D reconstruction allowed to validate the dynamics numerical simulator developed at Politecnico di Milano, Department of Aerospace Science and Technologies (PoliMi-DAER). The reconstruction of the trajectory of a flexible body, as the net is, while changing its configuration through cameras is very challenging. For this reason, a 3D reconstruction tool has been implemented in-house in Matlab. It performs color segmentation and stereo matching of the identified colored knots and iterative closest point for knots time tracking. The details of the algorithm can be found in [1].

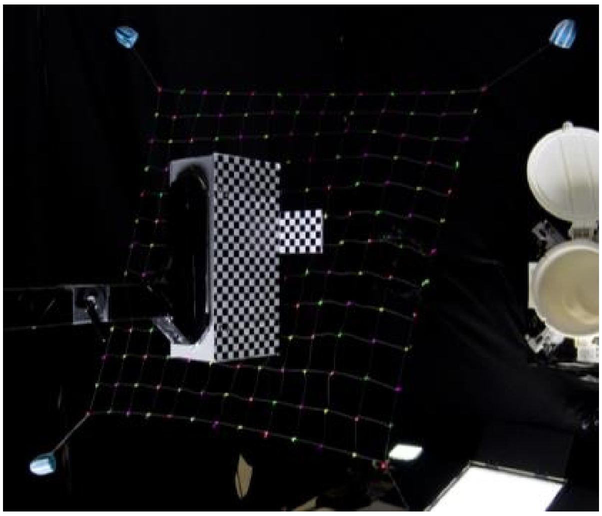

Figure 1: Patender - Experimental Setup

2.1. Results

All the main results have been already presented in [1]. In this paper, few images will be used to show some of the main achievements that have been reached. In particular, Fig. 2 shows the output of the image processing algorithm for the reconstruction of the net trajectory. Three snaps have been selected to show how the performances decrease in the last phase of the wrapping.

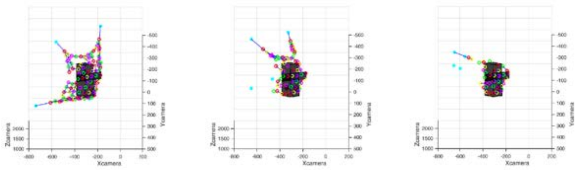

Figure 2: Wrapping Reconstruction

In Fig. 3, the drift between experimental and reconstructed data are presented. A statistical analysis was carried out. In fact, Fig. 3 shows maximum, mean and standard deviation of the relative drift. As expected, very good match was found during the deployment and first phase of wrapping. However, after the initial closure, the error increases, but still in an acceptable range, due to the bending neglecting in the model and to the difficulty in localizing knots in the images.

Summarizing, this first microgravity experiment, that was performed to validate net dynamics models, was successfully conducted. The parabolic flight allowed to increase the TRL of this capturing technology, proving its effectiveness and robustness. The results of the model validation shows a good match between experimental and simulated net trajectories. It is safe to say that after this experimental validation, the tool developed by Polimi can be used with acceptable accuracy to simulate flexible nets' dynamics in microgravity condition.

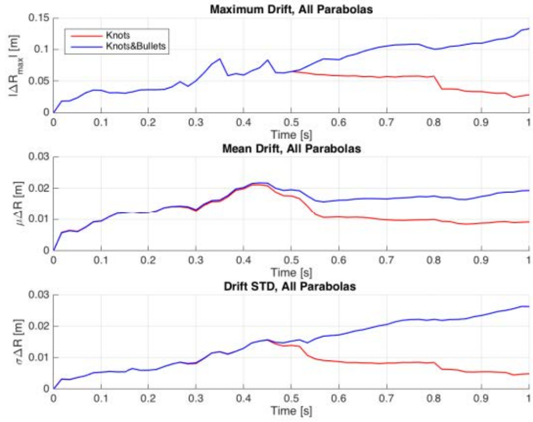

Figure 3: Numerical vs Experimental Results

3. SATLEASH EXPERIMENT

The SatLeash experiment was proposed to investigate the dynamics and control of tow-tethers, for space transportation. In fact, the study of tethered objects and their control is a key point when dealing with Active Debris Removal missions based on a net-capture mechanism. One of the main reason is because space tugs, made of a passive orbiting target interconnected through a flexible link to an active chaser imply new challenges for guidance and control design. For this experiment, an innovative wave-based control, using tension feedback, was proposed. This kind of technique represent an effective method to stabilize the system during tensioning and release phases. The team exploits the same multibody dynamics simulator, developed at PoliMi-DAER, that was used for the PATENDER experiment. The experiment was selected to fly in microgravity conditions by the ESA FlyYourThesis! 2016 programme. In the next paragraph, different tests to demonstrate the effectiveness of the control law are presented.

3.1. Scientific Background

The tethered tug concept was introduced by Aslanov and Yudintsev [2], [3] and Jasper and Schaub [4], [5]. In order to perform robust de-orbiting operations the chaser's GNC system has to be able of damping vibrations and avoiding instabilities of flexible elements. For this reason, a deeper understanding of the tethers three-dimensional behavior in microgravity is necessary. The proposed control law focuses on the avoidance of the most critical modes, in particular, whiplash (sudden rotation of spacecraft occurring right after the towing cable gets stretched) and bounce-back effects (whenever thrust is shut down, the tether slackens and the residual tension accelerates the two objects towards each other, leading to the risk of collision).

3.2. Wave-Based Control

The use of the wave-based control (WBC) for space application and in particular for space tethers was firstly proposed by O'Connor [6]. The strength of this control technique resides in its simplicity and robustness. In fact, its mathematical implementation is very straightforward and it does not require the exact knowledge of system flexibility to stabilize it. The main idea of the wave-based control is to interpret the axial elastic interaction between chaser and target as traveling mechanical waves. Hence, the chaser motion must be devoted to absorb the returning wave, introducing damping to the flexible system. In the Satleash experiment, the WBC has been implemented in its simpler form. With this formulation, the controller is a velocity control, with a proportional law between the tether tension and the damping velocity of the actuator. The details of the implementation has been previously presented in [7].

3.3. Dynamic Similitude with Scaled Model

The limited operational area of the Novespace Airbus A310 ZeroG imposed some constraints on the design of the experimental setup. For this reason, the SatLeash experiment was designed to reproduce a scaled on-orbit scenario. This can be achieved with a full dynamic similitude. The scaling methodology is hereby presented for clarity. As for any dynamic system, the physical free variables are forces, masses, length and time; on the other side, the free physical dimensions to be considered for scaling are the mass, the length and the time ([M], [L], [T]). Therefore, according to the Buckingham Pi theorem, a single π non-dimensional term suffices to ensure the dynamics similitude holding; in particular, the $\pi = MLF^{-1}T{-}2$ must be equal for the model and for the prototype, therefore, from the statement that $\pi_m = \pi_p$ the relationship to scale the forces is obtained:

$$S_F = \frac{S_M S_L}{S_t^2} = S_M S_a \tag{1}$$

with S_i scale factor and i the quantity referring to Force, Mass, Length, time and acceleration respectively. From equation 1 it is possible to derivate, exploiting the experiment, the actual forces of the real scenario. Depending on the experiment constraints and driver, actually, the mass, length and time scaling factors can be settled as variables dependent on more convenient quantities. In our case, a geometric similitude is imposed. In particular, using the Hooke's law and considering the strain scale equal to one, the scale of tension in the tether can be rewritten as:

$$S_F = S_\sigma S_D^2 = S_E S_\epsilon S_D^2 = S_E S_D^2 \tag{2}$$

where σ is the stress, ϵ the strain, E the Young's modulus and D the diameter. It is also remarked that setting tether modulus, diameter and length is equivalent to select tether stiffness. In fact:

$$K_t = \frac{EA}{L} \rightarrow \frac{S_E S_D^2}{S_L} \tag{3}$$

Considering the possibility of modeling the system as a second order system, the frequency scale becomes:

$$S_\omega = \frac{1}{S_t} = \sqrt{\frac{S_K}{S_M}} \tag{4}$$

Now, by combining eq. 1, 2, 3 and 4, it is possible to choose tether stiffness (i.e. E, D, L) and target mass and to exploit these equations to obtain the scale on all the other geometric, kinematic and dynamic quantities and map them from the experiment data to the in orbit application. Finally, once the system dynamics has been scaled, the manoeuvre parameters can be defined in terms of acceleration and ΔV and by consequence manoeuvre time, by combining the above relations with the kinematic relation for velocity as:

$$S_v = S_a S_t \frac{S_a}{S_\omega} = \sqrt{\frac{S_E S_L S_D 2}{S_M}} \tag{5}$$

The mechanical design of the experiment for both the main rack and the floating module, in flight configuration, is depicted in fig.4 and 5. The details of the implementations can be found in [7].

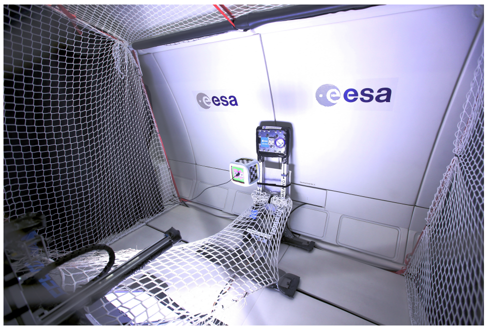

Figure 4: Floating Module

3.4. Control Strategy Validation

In this section, some representative results of the control strategy effectiveness are presented. The first reported test wants to demonstrate the effectiveness of the control in the mitigation of the vibration during the pulling phase. Fig.6 shows the effectiveness of the WBC on the system.

In 6 the blue line reproduces a parabola with $Z = 1000\frac{Kg}{s}$. With this value for the control parameter, the WBC effect on the system behavior can be assumed negligible. On the contrary, $Z = 10\frac{Kg}{s}$ has been selected to obtain the required performances by the controller. This value has been estimated by empirical assumptions and tests conducted exploiting a low friction table at Polimi premises. With different slack conditions, representative of different in-orbit, after capture conditions, the controller is able to absorb the vibrations anyhow, and it permits a considerable reduction of the overshoot. It is worth

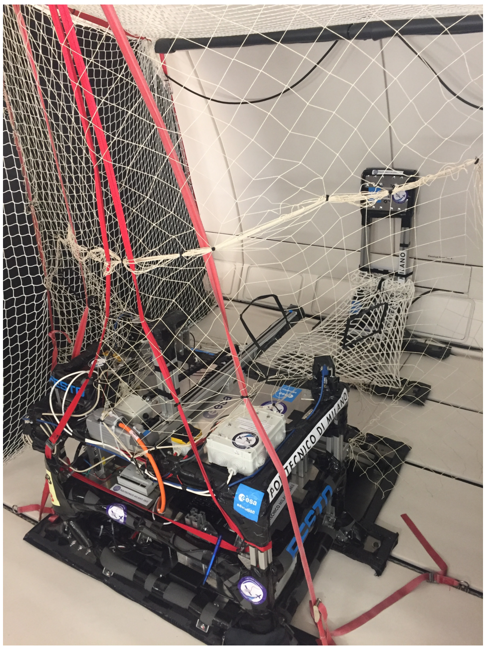

Figure 5: Experiment Configuration - Flight Mode

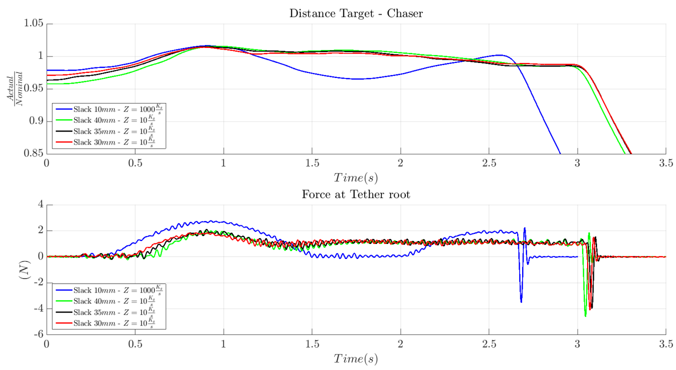

Figure 6: Stabilization Phase

notice how the WBC allows to obtain a tensioning of the tether at the end of the manoeuvre. It can be also seen that no collapsing of the tether occurs when a suitable parameter Z for the controller is selected. Instead, it is evident the collapsing of the tether without control. The second presented test case is used to show the effectiveness of the controller during the release phase, i.e. at the end of the pulling phase. Fig.7 shows how the WBC is able to correct the behavior of the system even in this phase. The partial absorption of the potential energy due to the elongation of the tether by the actuator allows the decrease of the final relative velocity between chaser and target. Moreover, the peak of tension present without control is considerably damped. Fig.7 also underlines an important feature of this control: the robustness. As already said, the mathematical and empirical estimation of the estimated optimal value is $Z = 10\frac{Kg}{s}$. The robustness of the controller has been tested by setting Z as 25% higher or lower than the optimal value. Also with these off-nominal conditions, the control performance are pre-

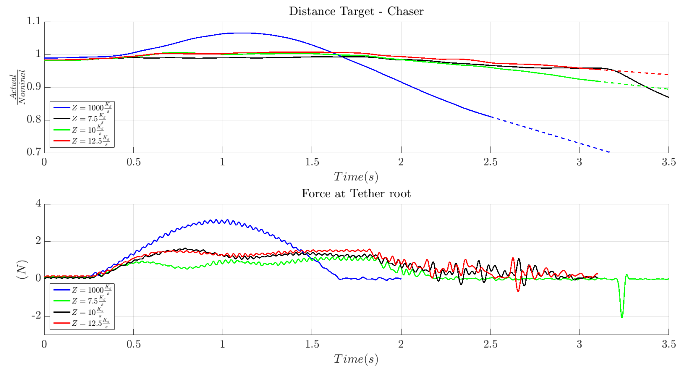

Figure 7: Release Phase

served.

4. CONCLUSION & FUTURE STEPS

In the last decade, the Department of Aerospace Science and Technology of Politecnico has drawn a clear roadmap towards the increase of the TRL of a net-based strategy for Active Debris Removal. The two parabolic flights PATENDER and SatLeash have validated the multi-body simulator developed at Polimi to describe the dynamics of flexible systems. Moreover, these experiments have tried to find and demonstrate the effectiveness of possible solutions to all the classical bottlenecks of a net-based system for ADR, i.e. the capture of the debris and the control of the tethered system. The ongoing projects at Politecnico di Milano, aim at testing the complete net-tether system for capturing and controlling an orbital debris. In particular, another parabolic flight experiment is currently under design. The goal of this experiment will be the study of the tether-net system after the capture phase and to verify its ability to damp the rotational motion of a tumbling object. Concluding, net capturing devices and tethers, their dynamics and system design, were deeply studied at Politecnico di Milano, Department of Aerospace Science and Technologies, and by now they have acquired a high level of design maturity, being ready to the next phase of technology development (orbital/sub-orbital flight).

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