# GNC TECHNIQUES FOR PROXIMITY MANOEUVRING WITH UNCOOPERATIVE SPACE OBJECTS

*R. Benvenuto, M. Lavagna*

Politecnico di Milano, Department of Aerospace Science and Technologies,
Via La Masa 34, 20156, Milano, Italy

## ABSTRACT

Active debris removal and satellite servicing are current hot spots in space research, dealing with fully or partially uncooperative orbiting objects to be approached and captured autonomously by another space vehicle. These tasks entail a high level of autonomy during proximity manoeuvring and docking/grasping, hence defining new challenges for Guidance, Navigation and Control. To perform these tasks, different techniques are currently being proposed in literature, starting from the robotic arm to grasp the target to tethered-nets to wrap it. From dynamics point view, these technologies differ for the flexibility involved in different elements and connections.

Validated simulation tools describing multibody dynamics, and their stabilization via control laws, are considered of primary importance to design future missions. At Politecnico di Milano, Department of Aerospace Science and Technologies, a validated software tool was developed to describe the multibody dynamics involved in these scenarios and to enable fast analysis and guidance and control law design and testing. Experimental activities are also on-going to validate the developed dynamics models and test the implemented control laws.

In the paper, an overview is given on the abovementioned multibody dynamics tool and on the scenarios it can deal with; additionally their validation process and analysis output are presented, for both rigid and flexible techniques.

***Index Terms—*** active debris removal, satellite servicing, proximity manoeuvring, dynamics models validation, control testing

## 1. INTRODUCTION

Active debris removal and satellite servicing are some of the current hot spots in space research: plenty of engineering challenges, they deal with fully or partially uncooperative orbiting objects to be approached and captured autonomously by another space vehicle. The Active Debris Removal (ADR) topic focuses on trading-off, designing and making operational mechanisms placed on board an active chaser that can rendezvous with and grapple an inert and tumbling target, to eventually change its dynamics transferring it to a disposal orbit. Recent studies run by NASA [1] and ESA [2] revealed that the environment can be stabilized if objects in the order of 5 to 10 per year are removed from space; more, the priority debris list follows the more massive in highly inclined orbits the more urgent rule being, in such a case, ADR more effective in collisions occurrence and dangerous cascade effects reduction. On the other hand, on-orbit satellite servicing (OOS) deals with refuelling and/or maintenance of active spacecraft, and therefore supposed to be partially cooperating, to be approached and docked by the active chaser to carry out the needed operations when connected. OOS could significantly increase the lifetime of a considerable number of satellites, which was shortened by malfunctions occurring during operational period [3]: concepts of various possible missions devoted to servicing of low Earth orbit (LEO) or geostationary Earth orbit (GEO) satellites are being developed [4], [5].

To perform these tasks, different techniques are currently being proposed in literature, starting from the robotic arm to grasp and control/de-tumble the target [6], which can deal with both ADR and OOS, to capturing-nets to wrap it [7] and towing-tethers to transport it [8], techniques more adapted for ADR. From dynamics point view, these technologies differ for the flexibility involved in different elements and connections. A general-purpose system design should effectively intervene on objects different in configuration, materials and possibly in dimensions.

ADR and OOS tasks define new challenges for Guidance, Navigation and Control (GNC): these missions cannot be tele-operated and ground-controlled due to communications delays, intermittence, and limited bandwidth between the ground and the chaser. Therefore, there is substantial interest in performing these operations autonomously: the research work, here presented, moves in that direction and have the main objectives of

- developing fast, reliable and validated dynamics models, to drive ADR and OOS systems design and support GNC implementation, including the flexibility modelling and contact dynamics of capture mechanisms and coupled stacks configurations;
- implementing GNC laws adapted to perform the involved operations, from approaching to

removal\servicing, to demonstrate mission feasibility and increase the level of autonomy;

- validating dynamics models and control laws through experimental activities, including microgravity campaigns and hardware-in-the-loop testing.

At Politecnico di Milano, Department of Aerospace Science and Technologies (PoliMi-DAER), a validated software tool was developed to describe the multibody dynamics involved in these scenarios and to enable fast analysis and guidance and control law design and testing. Experimental activities are also on-going to validate the developed dynamics models and test the implemented control laws. In section 2 of the paper the developed multibody dynamics simulation tools are presented; an overview on different scenarios dealt by the simulator is given in section 3, 4 and 5, respectively on tethered-tugs, capturing nets and robotic arm: in each of these sections analysis and simulation output are presented and their validation process is discussed. Finally, in section 6 results are discussed and conclusions are drawn.

## 2. MULTIBODY DYNAMICS SIMULATION ENVIRONEMENT

The multibody simulation environment, developed in house at PoliMi-DAER, provides a fast and accurate simulation environment to describe multiple bodies' six degrees of freedom dynamics, possibly linked by different flexible/rigid connections and including flexible appendages, propellant sloshing: the toolbox was originally implemented under an ESA contract [9], i.e. MUST: Multibody Simulation Tool for active satellite servicing. Since that work, several researches were conducted and upgrades of the simulator were also implemented afterwards at PoliMi-DAER to add a detailed environmental model to account for all the relevant perturbations, especially at low altitudes; to model the deployment and wrapping dynamics of flexible nets around targets, with the inclusion of collision detection and contact dynamics algorithms [10], [11]; to model the electrodynamics effects on conductive tethers (i.e. EDTs) operating in the ionosphere [12]; to model space-based robotic manipulators.

The tool was developed to describe the multibody dynamics involved in ADR\OOS scenarios and to enable fast analysis and guidance and control law design and testing. The tool is also well suited as a functional simulator hardware-in-the-loop (HIL) test facilities implementation and tuning.

Fully integrated in Matlab/Simulink, the toolbox is based on SimMechanics multibody software [13]: the use of this platform allowed to incorporate in one environment all the elements essential in numerical simulations of net, tethers and robotic manipulators dynamics. SimMechanics' solver works autonomously and creates the physical network from the block model of the system. The system of generalized equations of motion, represented in Eq. 1 in the most general form to account for presence of tethers or robotic manipulators, is then constructed and solved in Simulink:

$$[M(q)]\{\ddot{q}\} + [D(q,\dot{q})]\{\dot{q}\} + [K(q)]\{q\} + \{C(q,\dot{q})\} + \{G(q)\} = \{Q_{GNC}\} + \{Q_{dist}\} \quad (1)$$

where q is a state vector and includes satellite's states and manipulator's states, M is a mass matrix, D a damping matrix, K stiffness matrix, C is a Coriolis/centripetal force vector, G is a gravity force vector, $Q_{GNC}$ is a vector of generalized control forces acting on both satellite and manipulator, $Q_{dist}$ is a vector of generalized disturbing forces.

The software is implemented as a combination of Matlab functions and Simulink building blocks libraries; in Figure 1 the last is depicted. An interesting implemented functionality, as described in [9], is the possibility of automatically constructing Simulink/SimMechanics mechanical models from Matlab scripts.

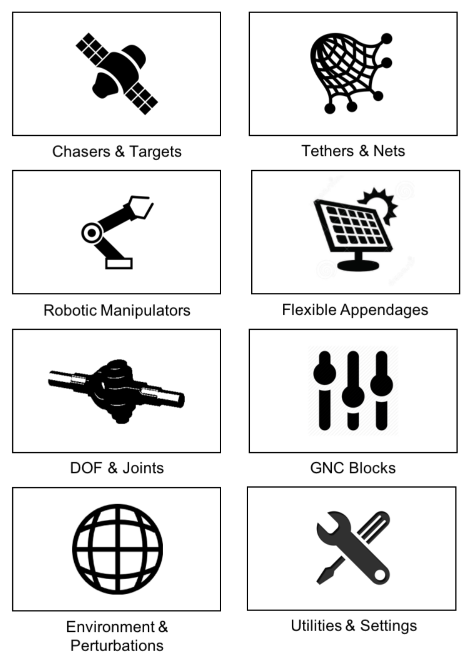



**Figure 1. Simulink library of building blocks**

The analysis of tethered systems and flexible elements (as appendages) is performed using discrete-mass representations or lumped parameters methods (being compatible with the SimMechanics environment [14]). By contrast with computationally intensive methods as continuum models - that usually consider partial differential equations - or finite element models - that can produce high-

accuracy results but their proper implementation can be difficult, especially for multiple tethers as in netted systems – flexible systems discrete-mass representations are used frequently (for example in [15], [16], [17]): they are able to model higher-order tether modes while capturing end-bodies motion on both ends of the tether. The dynamics behaviour can be adequately described, obtaining an approximate solution for tether flexing and whipping but allowing a fast computational environment, particularly adapted to synthetize and test guidance and control laws. Moreover, these models allow to describe the system parametrically, to treat different configurations and include different viscoelastic laws: for example, two laws (namely the linear Kelvin-Voigt law and the non-linear Hunt-Crossley law) are implemented in the simulator for material tension and contact dynamics ([9], [11]).
Conceptual representation of lumped models is presented in Figure 2, while detailed equations are reported in [10] and [11]: it is remarked that while the first model is only able to describe axial stiffness (but allows not to consider compression as it is for tethers), the second can also account for bending and torsion.

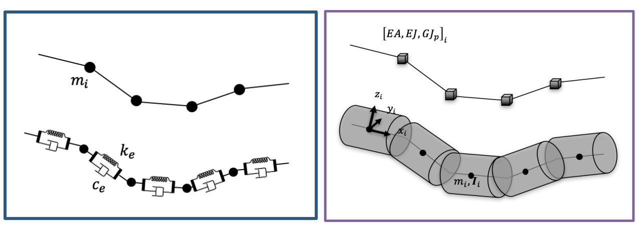



**Figure 2. Lumped models conceptual representation**

## 3. TETHERED-TUGS

### 3.1. Scenario overview

Towing objects in space through tethers is becoming an appealing concept for many missions, such as Active Debris Removal, LEO satellites disposal, low-to-high energy orbit transfer and even asteroids retrieval. Space tugs are made of a passive orbiting target interconnected through a flexible link to an active chaser the thrusters of which excite the stack dynamics. The concept is represented in Figure 3.

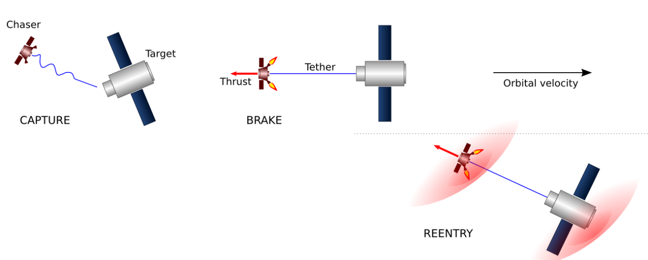



**Figure 3. Tethered-tug concept**

A large body of work exists on the dynamics of tethered space systems, but in general past researches have focused on momentum transfer tethers or electrodynamics tethers, studying relatively stable tether manoeuvring, as retrieval and deployment, and assuming the secondary body far less massive than the primary [18].
The tethered tug concept itself was firstly studied by Aslanov and Yudintsev [8], [19] and Jasper and Schaub [20], [21], [22], who independently studied different control techniques using a simplified simulation environment.
The chaser's GNC system is required to robustly perform de-orbiting operations while controlling a complex system and damping vibrations of flexible elements and connections, avoiding instability, collisions, and tether entanglement. Due to flexibility, zero gravity environment and coupled end-bodies dynamics, tethered-systems undergo a complicated set of three-dimensional librations and vibrations. The most common critical modes that may arise during towing operations are whiplashes (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, increasing the risk of collision) [23]. After these modes, the control recovery is more difficult and not always possible. The tether may entangle on the target or the chaser itself and, hence, break. Adapted GNC laws are then necessary to avoid these modes.

### 3.2. GNC analysis and design

In [24], the authors demonstrated a method to recover control after a bang-off thrust profile through feed-back control using reaction control systems, pulse width modulation and relative distance/tension sensors. However, this method presented criticalities in letting the tether slacken after the burn, which may lead to entanglement and breakage, especially if the target angular motion is not completely damped.
Recently several techniques have been proposed to stabilize the system during towing. Among them, methods using feed-forward input shaping of the pulling thrust profile seem particularly interesting (in [22], a notch filter was used to obtain a continuous modulation of the thruster and compared to a Posicast controller for discrete modulation). These methods are able to stabilize the system both at the beginning and at the end of the pulling phase by cutting off the first mode frequencies of the tethered-system: whiplashes are avoided through gradual tether tensioning and the bounce back is greatly decreased (an almost null relative velocity, between the bodies at the end of the thrusting phase, can be achieved).
The model used in the following simulations is depicted in Figure 4: the red body represents the controlled chaser,

while the blue one is the passive target. The system parameters are reported in Table 1. Such a model doesn't take into account any grasping technique: the tether connection points are fixed on the bodies' external faces and no slippage is considered. Tether elasticity and damping are the key parameters playing the fundamental role in the flexible dynamics behaviour.

| | |
|---|---|
| **Chaser Mass [kg]** | 1300 |
| **Target Mass [kg]** | 5000 |
| **Initial orbit altitude [km]** | 600 |
| **Thrust [N]** | 800 |
| **Tether Young's modulus [GPa]** | 32 |
| **Tether damping factor [-]** | 0.1 |
| **Tether length [m]** | 60 |
| **Tether diameter [m]** | 0.003 |

**Table 1: Towed de-orbiting simulations parameters**

The $\Delta v$ applied is 160 m/s: with this the flight path angle reached at 120 km of altitude (i.e. atmospheric interface)) is -1.6°, respecting the requirements on massive bodies controlled re-entry. Based upon input-shaping method, this can vary the thrusting duration: for a bang-off step input profile the burn duration is 1300 s.

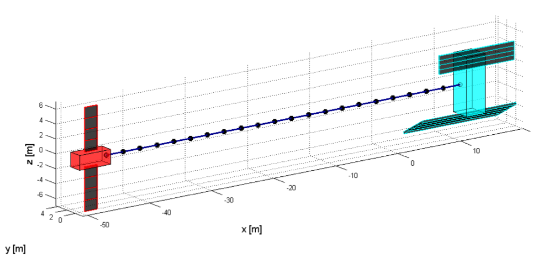



**Figure 4. Multibody model used for simulations (20 nodes tether discretization)**

During towing, the Chaser has active attitude control to ensure the thrust vector points in the desired direction: the feedback controller used for the simulations is a regulator centred around the quaternion error feedback of the vehicle attitude [29]. The control input u has the form in Eq. 2:

$$u = \omega_C \times I_C \omega_C - D\, \omega_C - K\, q_e \tag{2}$$

where $q_e$ is the error quaternion and $\omega_C$ the chase angular velocity. K and D are selected to be multiple of the spacecraft inertia and related to controller bandwidth and damping factor by the following relations:

$$K = \omega_{BW}^2 I_C \tag{3}$$

$$D = 2\xi \omega_{BW} I_C \tag{4}$$

*3.2.1. Input shaping and command smoothing techniques*

Shaped thrust profiles can be designed such that the primary natural frequency of the flexible body is not excited by the control input. Numerous researches have worked to provide solutions to the the challenging problems posed by the flexible dynamic systems, for example in cranes rest-to-rest control. The work can roughly be broken into three categories: feedback control, input shaping and command smoothing. Input shaping can effectively reduce the oscillatory dynamics of many types of flexible dynamic systems and it works as follow: to eliminate the oscillatory response, the original command is convolved with a series of impulses, called the input shaper, to create the shaped command; the shaped command can move the system without inducing vibrations [30].
For a three-impulse zero vibration and derivative (ZVD) shaper, the amplitudes, $A_i$, and times, $t_i$, of the impulses are given in Eq. 5:

$$\begin{bmatrix} A_i \\ t_t \end{bmatrix} = \begin{bmatrix} \frac{1}{1+2K+K^2} & \frac{2K}{1+2K+K^2} & \frac{K^2}{1+2K+K^2} \\ 0 & 0.5T_d & T_d \end{bmatrix} \tag{5}$$

where $T_d$ is the damped period of vibrations and K is function of the damping ratio $\xi$, as expressed in Eq. 6:

$$K = e^{(-\xi\pi/\sqrt{1-\xi^2})} \tag{6}$$

The convolution is performed by simply multiplying the original command by the amplitude of the first impulse, and adding it to the original command multiplied by the amplitude of the second impulse and shifted in time by one-half of the damped vibration period, and then adding it to the original command multiplied by the amplitude of the third impulse and shifted in time by a damped vibration period. Note that the rise time of the shaped command is increased by the duration of the input shaper.
On the other hand, command smoothers filter the input to produce a smooth profile that reduces vibration: in [31] a proposed smoother, function of the system parameters, such as natural frequency and damping ratio, is described; it is particularly interesting for this problem because its robustness to modelling errors in natural frequency and damping can be easily increased and demonstrated to be effective. The transfer function of the smoother is presented in Eq. 7, in the Laplace domain:

$$G(s) = \frac{\xi^2\omega^2}{(1-M)^2} \frac{(1-Me^{-T_d s})^2}{(s+\xi\omega)^2} \tag{7}$$

and is function of the modelled damping ratio $\xi$, the modelled natural frequency $\omega$ and the damped period of vibrations $T_d$; the term M id equal to $K^2$, as reported in Eq. 6.

*3.2.2. Simulation results*

The above-mentioned shapers have been used to modulate a step input profile in order to damp the axial vibrations of the tether, with the objective of reducing the relative velocity at the end of the burn phase, therefore decreasing the bounce back. Their outputs have been compared to the non-modulated step input, as a benchmark.
To find the system first mode frequency, an eigenvalue analysis is done on the dynamics matrix of a simplified one-dimensional model with a single mass discretization for the tether and no damping. The dynamics of such simplified system can be easily written in state-space form: in [22] it was demonstrated that by increasing the tether discretization nodes the first mode frequency (being the one to damp, containing most of the energy) does not vary significantly. With the parameters reported in Table 1 the frequency is found to be equal to 0.3 Hz and results of the step input profile (Figure 5) confirms the theoretical result.
Results show the input command and the relative distance evolution between the two bodies for the three profiles: Figure 5 step input, Figure 6 ZVD shaper (Eq. 5), Figure 7 Command smoother (Eq. 7).

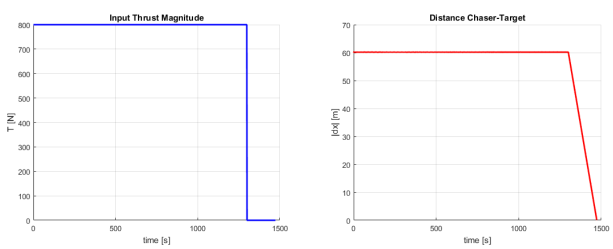



**Figure 5. Input step profile and relative distance evolution**

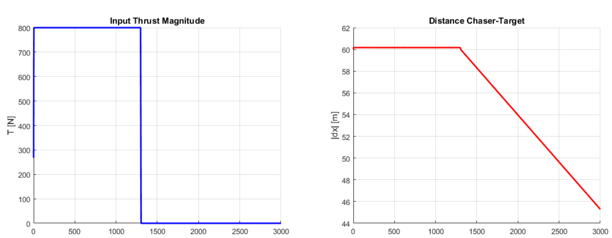



**Figure 6. ZVD shaped profile and relative distance evolution**

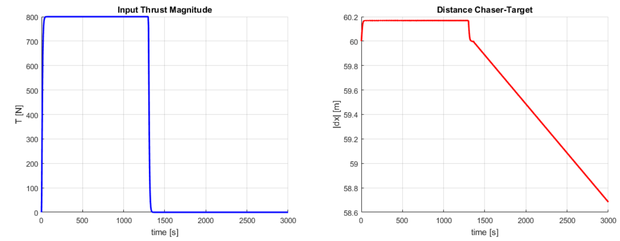



**Figure 7. Smoothed profile and relative distance evolution**

With a non-modulated thrust (Figure 5), the bounce back is clearly visible and collision occurs about 200 s after the thrust is shut down. The ZVD shaper produces a discretized thrust profile (the thrust is turned on and off by three steps, Figure 6); it is able to significantly damp the residual motion between the two bodies at the end of the burn: about 1700 seconds after the thrust is turned off the distance between the bodies is 45 meters. The command smoother uses a thrust profile that is continually modulated (Figure 7) and presents better performances with respect to the ZVD shaper, being the final distance around 58 at 1700 seconds after the burn. However, an important remark is necessary on the output of shapers and the possibility to obtain it using conventional orbital thrusters. With a continuous modulation the thruster throttle is assumed to be capable of achieving all thrust magnitudes that are commanded: this is unrealistic for high-thrust engines which are only able to operate in on-off control modes. Because of this fact, a discretized thrust appears more feasible: it assumes the tug to have several thrusters that can be fired independently, therefore increasing or decreasing thrust by steps.
Being the scale of results in Figures 6 and 7 not adapted to appreciate the difference between the differently-shaped input thrust profiles, an example is reported below in Figure 8 for a unitary step input of 10 seconds duration: here it is possible to clearly identify the difference between the two strategies.

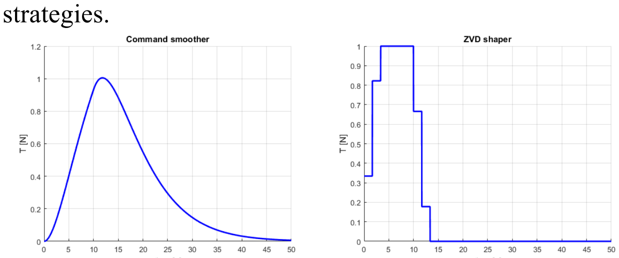



**Figure 8. Comparison between command smoother and ZVD shaper**

### 3.3. Experimental validation

The Fly Your Thesis! programme of the European Space Agency's Education Office offers university students the opportunity to conduct their scientific experiments in microgravity conditions, during a parabolic flight campaign.

In this framework, the PoliTethers team, from PoliMi-DAER, was selected to fly an experiment on-board Novespace's Zero-G aircraft, the flight campaign being scheduled for October 2016.
The SatLeash experiment[1] is going to investigate the dynamics and control of tow-tethers, for space transportation: the in-flight experiment focuses on validating the above-described models and verifying the implemented control laws. A reduced-scale tethered floating test-bed is going to fly equipped with a stereovision system to reconstruct its 3D trajectory and acceleration/tension sensors. Different tether stiffness will be tested as well as differently-shaped open-loop thrust profiles to verify their effectiveness in reducing bouncing-back effects. A schematic of the designed experiment is depicted in Figure 9.

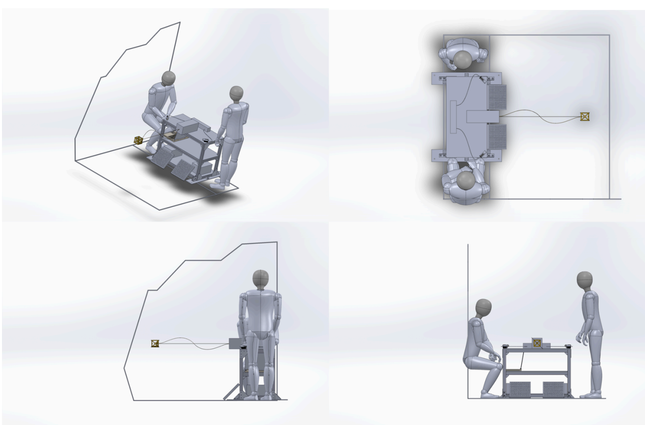


**Figure 9. SatLeash experiment configuration**

## 4. NET CAPTURING DEVICES

### 4.1. Scenario overview

The above-presented tethered-tug technique does not take into account the target grasping/capturing methodology. Several capture systems have been proposed that establish a flexible tethered connection between the two bodies (i.e. harpoons, tentacles, controlled floating gripper robots, etc.): among them, the use of throw-nets has been advocated as one of the preferred solutions: a flexible capture net is cast from an active satellite by impulsively accelerating a number of flying weights, hereinafter named bullets, attached to the net mouth; then the relative trajectory of the bullets deploys the capture net gradually during the flying process; finally, the net wraps the debris element, closes around it and thanks to the active chaser, tethered connected with the net, drag it to the disposal location in space. The concept of tethered-net satellite capture is represented in Figure 10.

The advantages of tethered-net systems are traceable in the higher interfaceability towards unknown targets' physical and dynamics characteristics, isotropic loads and safer capturing distances with respect to the robotic arm capturing technique. Furthermore, in contrast with rigid capture systems, these capture techniques do not need fine relative attitude control (the net can be shot almost independently of target relative attitude and tumbling, relying on the impact and entanglement for capture and on the friction for relative motion/tumbling dissipation). They also allow not to considering the centre of gravity alignment with thrust axis as a constraint, as it is for any rigid link solution: pulling the target instead of pushing it, as in the case of rigid connections, makes the system once again independent of target attitude, because the pulling force distributes along the tether and is always inline with the target centre of mass. On the other hand, these techniques are characterized by the difficulty in robustly detect the capture and closure occurrence after the impact and by settling a flexible tethered connection between the chaser and the target, with all the pros and cons described above.

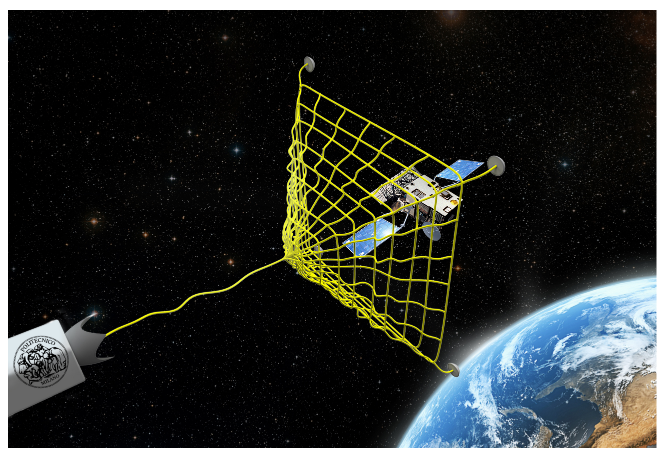


**Figure 10. Capture net concept**

The system was firstly studied by Astrium from a systemic point of view, in the ROGER study [25]. More recently, the e.Deorbit study [7], [26] was conducted by ESA's Concurrent Design Facility (CDF) within the Clean Space Initiative on a system design for the most promising ADR options. The net-tether option was selected as one of the suitable candidates and a preliminary system design was carried out. Recently, Huang et al. [27], introduced the Manoeuvring-Net Space Robot System, where bullets or flying masses are substituted by small controlled vehicles able to actively control the net trajectory and deployment,

[1] http://www.esa.int/Education/Fly_Your_Thesis/Meet_the_teams_PoliTethers_team

increasing the reliability of this system with respect to the purely passive ones.

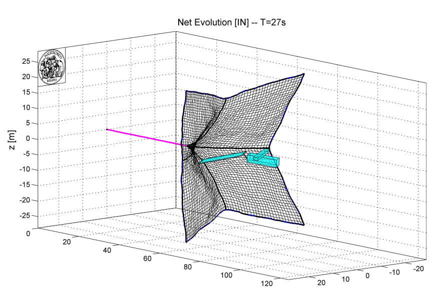
### 4.2. Net simulations and analysis results

The net deployment and impact dynamics have been studied in detail in the past few years ([10], [11]). In [10] a closing mechanism was designed with reels inside the bullets, controlled to wind up a cable on the net mouth to firmly close it around the target. Furthermore, in [11] it was demonstrated that during towing, the friction between the net and the captured target is able to damp the target residual angular motion stabilizing its attitude with respect to the tethered system.

As far as control is concerned, the net is an almost completely passive mechanism: the chaser is required to reach a precise position along track, relative to the target, and to cast the net with the correct conditions while maintaining a certain fixed attitude with respect to the target (to this end an LQR controller is used in simulation for position control while the attitude is controlled via the law detailed in Eq. 2). When the net is shot the position control is turned off and no compensation of the net shooting reactions on the chaser is performed: the vehicle is left free to drift, being the net casting conditions designed to account for that and the shooting time too short to use feedback control.

In the above-mentioned papers, several net topologies and geometries were also analysed to design the capture system, it was underlined how capturing with planar nets mostly rely on impact and entanglement while the closure mechanism may be more reliably used on 3D nets (i.e.) conical that are able to wrap the target before impacting with it.

In Figure 11 an example of simulation output is reported for the Envisat capture scenario: the spacecraft is simulated to be tumbling at 5 deg/s around H-bar axis (out of plane). The net is a 55x55 meters planar net with 1 m square mesh, deployed by four bullets shot at 5 m/s; the total system mass (net, tether and bullets) is 8.3 kg. The synchronization of the net deployment with the target angular motion strongly affects the closing behaviour. The simulations are also useful to design the system by computing the internal forces on threads and the contact forces during wrapping.



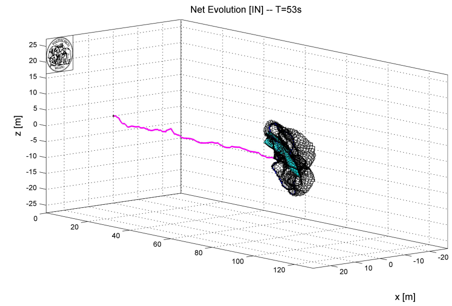




**Figure 11. Envisat capture simulation**

### 4.3. Experimental validation

A microgravity experimental campaign run within the ESA-sponsored ESA-PATENDER Study [28] (in consortium with GMV Spain and Prodintec Spain) and was performed to validate the net dynamics simulator in terms of both flexible dynamics and contact dynamics models. The experiment was successfully conducted on June 9$^{th}$ 2015 in the Novespace 116$^{th}$ parabolic flight campaign (62$^{nd}$ ESA Parabolic Flight campaign) on-board an Airbus A310 ZERO-G aircraft. The parabolic flight experiment also allowed raising the technology readiness level (TRL) of space throw-net techniques to TRL 5 (i.e. representative scaled model tested in a relevant environment): the representativeness was guaranteed by dynamically scaling the net with respect to an orbital reference scenario, as reported in [28]. The net, stored in a canister, was deployed by shooting massive bullets hanged on the net corners and high-speed high-resolution camera system (two stereo pairs) tracked the flexible system dynamics evolution, in order to allow the 3D reconstruction of the deployment and wrapping around the target phases. To reconstruct the trajectory of a flexible body, as the net is, while changing its configuration (deployment and wrapping around the target) through stereo-vision sensors, was a tough challenge that required appropriate means and fine tuning of the reconstruction algorithms. To answer the goal, a 3D reconstruction tool was implemented in-house at PoliMi-DAER revisiting the Matlab image processing Toolbox to answer the specific experiment data needs; in particular, the algorithm performs image processing for colour segmentation (net's knots were colour-coded with fluorescent pigments), stereo matching of the segmented knots and iterative closest point for knots time tracking. Of the visible knots 96% were correctly identified, limiting the manual work and allowing for an automatic reconstruction procedure. The target mock-up position and attitude were also reconstructed using chessboard markers applied to it.

In Figure 12, the output of the net trajectory reconstruction tool is depicted for one single frame (when the net is impacting with the target mock-up), and compared to the acquired image from one of the two stereo couples.

The corresponding simulation is reported in Figure 13, while contact forces and internal stresses are reported in Figure 14.

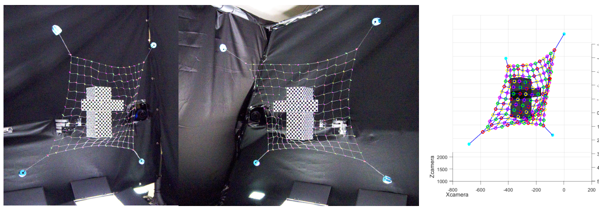


**Figure 12. Net trajectory 3D reconstruction of parabolic flight experiment**

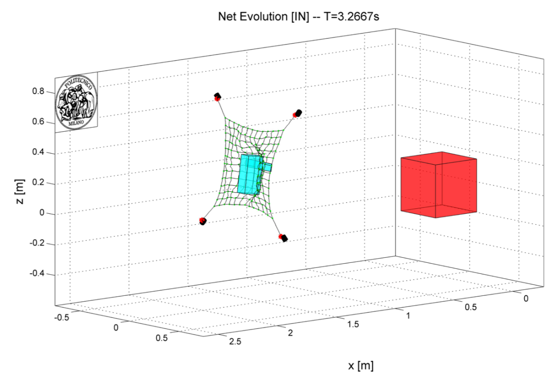



**Figure 13. Scaled simulation for parabolic flight test**

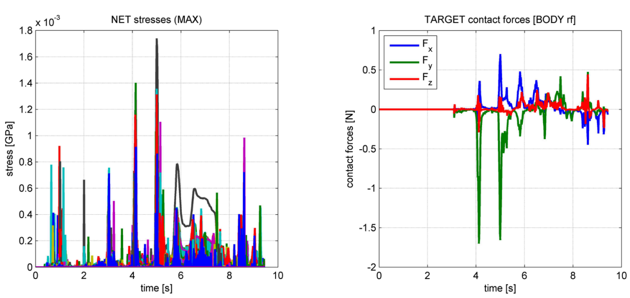



**Figure 14. Computed stresses and contact forces**

The 3D reconstruction results are currently being finalized and the next step will be their comparison with simulation results to validate the above-mentioned dynamics numerical simulator developed at PoliMi-DAER, conceived to support the design of tethered-net systems for ADR.

## 5. ROBOTIC ARM SCENARIO

### 5.1. Scenario overview and GNC design

Robotic manipulators are the most straightforward technique for OSS and they can obviously be applied to ADR. Many studies were carried out on the arm dynamics, its coupling with the base platform and its interaction with the non-cooperative vehicle ([6], [32], [33], [34], [35]).

By contrast with tethered-nets, the robotic arm solution is actively controlled throughout all the phases: the chaser is controlled relative to the target in position and attitude and also needs to compensate for the arm motion. In the case of tumbling targets, the chaser GNC needs to be able to autonomously coordinating the chaser angular motion with the target one (i.e. relative angular velocities need to be annulled).

The approaches to compensate the base motion due to arm's movements, typically fall into two categories:

- use fixed-base arm control strategies but maintain the attitude of the vehicle using thrusters or reaction wheels;
- let the vehicle drift but modify the path of the arm to compensate for the base motion.

The first approach is called *coordinated control* and has the advantage of decoupling the manipulator from the satellite control but at the cost of increased fuel/power consumption [34]. The latter method, called *internal motion control*, uses less power but requires a more complex strategy for controlling the arm [35]. A coordinated control between the chaser and the arm has been preferred here, when dealing with a fast tumbling target. In the post-capture phases a coordinated control between the arm and the chaser is also needed to stabilize and de-tumble the stack, to be able to later carry out the needed operations.

By using a coordinated control strategy, the arm control is decoupled from the chaser control. The chaser vehicle relative position is controlled through an LQR and its attitude through the eigenaxis control law using quaternions that has been presented in Eq. 2. (appropriate controller gains are selected internally based on errors). The chaser guidance feeds forward a signal to the arm PD controller: the manipulator can be controlled in joints coordinates or Cartesian coordinates (an inverse kinematics solver has been included in the manipulator model). The arm trajectory can be designed off-line or constrained by the final state of the end-effector/gripper which should be the same as the grappling interface at the moment of contact. In the second case, the reaction torques on the chaser vehicle are always bigger, to compensate for the arm reactions.

Four guidance phases are distinguished:

- the chaser reaches a no relative motion condition with respect to the target, at a safe fixed distance;
- the arm is deployed (the end effector is moved to a certain point) and the chaser final approached is executed towards the grasping point: for this manoeuver a straight line trajectory (in relative frame) was adopted to ensure obstacle avoidance;

- the contact and grasping part in which the gripper is controlled using torque feedback to keep a constant grasping force (*rigidization*);
- de-tumbling and movement of the captured target towards the mechanical locking with the chaser.

The authors are planning to test the implemented GNC laws on an air-bearing facility to finalize the test and validation work presented so far.

### 5.2. Analysis and simulation results

In Figure 15, the robotic arm modelled scenario, used in the following test case, is represented.

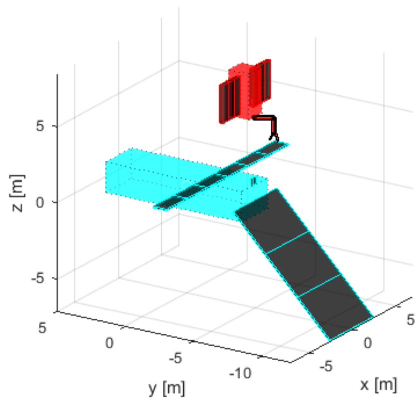



**Figure 15 Robotic-based capture – modelled scenario**

In the presented analysis, each link of the robotic arm is modelled as rigid. However, the toolbox allows to model the flexibility of each links by using the model depicted in Figure 2 on the right (including axial, bending and torsional contributions).
In Table 2 simulation parameters are reported:

| | |
|---|---|
| **Chaser Mass [kg]** | 1450 |
| **Target** | Envisat |
| **Target angular velocity [deg/s]** | 3.5 |
| **Arm Mass [kg]** | 30 |
| **Arm links [#]** | 2 + Gripper |
| **Arm DOF [#]** | 4 |
| **Forward reach [m]** | 3.1 |
| **Control set-point rate [Hz]** | 10 |
| **Joints angular accuracy [deg]** | 0.3 |

**Table 2: Robotic arm scenario simulations parameters**

Preliminary simulation results of the above-described second guidance phase are presented below: at the beginning of the simulation the chaser is supposed to have already reached a condition of null relative motion with respect to the target, i.e. correctly aligned at the safety distance.
Chaser controller output, in terms of chaser control forces and torques, is reported in Figure 16, in chaser body frame. In Figure 17 joints' angular errors and computed joint torques are shown. The results demonstrate the performances of the implemented coordinated control.

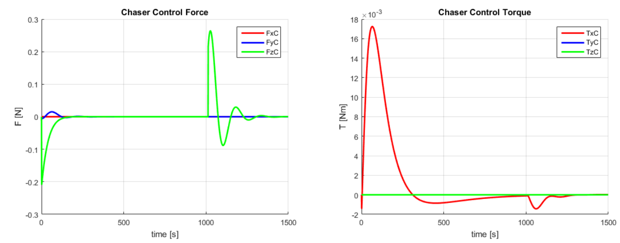



**Figure 16. Chaser control forces and torques (chaser body frame)**

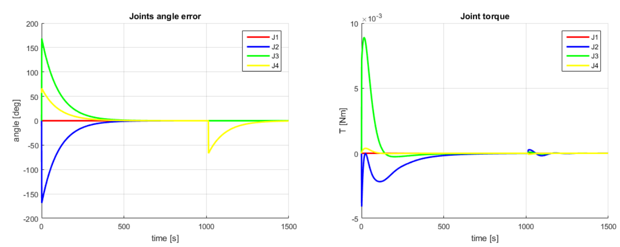



**Figure 17. Joints angle errors and joints torques**

Finally, in Figure 18 the distance between the location of the grappling point on the target and the arm's gripper tip is presented: it can be used as an error estimate of the grasping (occurring at about 1200 second). The obtained accuracy is below 1 mm.

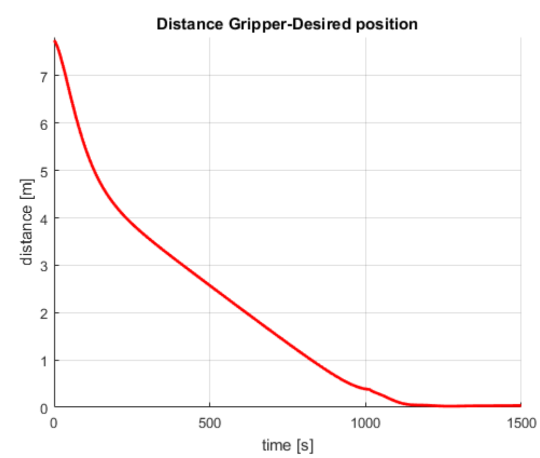



**Figure 18. Distance between between grappling point and gripper location**

## 6. CONCLUSION AND DISCUSSION

The development of a validated multibody software tool, to describe active debris removal and on-orbit satellite servicing systems' dynamics, has been presented in the paper. The simulator has proven to be particularly adapted to support the guidance, navigation and control design and testing, as well as to support system design. In particular, the focus was put on towing tethers for orbital transportation, net capturing devices and robotic arms/manipulators, on their dynamics analysis and control synthesis. The development of a chaser satellite able to perform autonomous servicing/removal mission is a complex, multidisciplinary and challenging task: such missions require utilization of many sophisticated technologies and reliable lightweight manipulators capable of capturing objects which are not equipped with dedicated docking ports.

As far as the tethered-tugs are concerned, control methods based on feed-forward shaping of the pulling thrust proved to be effective in simulation, stabilizing the system by cutting off the tethered-system's first modes frequencies, significantly reducing the bounce back. The next step will be their test in the following ESA's Fly Your Thesis! parabolic flight campaign.

Net capturing devices, 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). The parabolic flight campaign, that was performed to validate net dynamics models, was successfully conducted and the net 3D trajectory was properly reconstructed (the model validation is currently on-going). The test campaign also allowed to increase the TRL of this capturing technology, proving its effectiveness and robustness.

Finally, an overview on space-based robotic manipulators was given: a coordinated control strategy for target capturing was also discussed and its performances were demonstrated through simulation.

The techniques discussed in the paper significantly differs when it comes to guidance and control requirements of the chaser vehicle, throughout the operations of capture and target stabilization: a preliminary answer to these requirements was given in the paper, together with an outline of experimental models validation and control testing activities.

## 7. ACKNOWLEDGMENTS

The authors acknowledge the European Space Agency TEC-ECN and TEC-MMA divisions for supporting studies related to the topic here discussed.

The authors acknowledge that the net trajectory reconstruction experimental results were obtained within the ESA-sponsored ESA-PATENDER Study, in consortium with GMV Spain and Prodintec Spain.

Finally, the authors acknowledge the European Space Agency's Education Office for the recent selection on the Fly Your Thesis campaign, as well as the PoliTethers team who are currently designing and implementing the experiment.

## 8. REFERENCES

[1] Liou J.C. and Johnson N.L., "A sensitivity study of the effectiveness of active debris removal in LEO", in Proc. 58th IAC 'International Astronautical Congress' (IAC-07-A6.3.05), Hyderabad, India, 2007.

[2] Bastida B. and Krag H., "Analyzing the criteria for a stable environment", in Proc. 2011 AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, 2011.

[3] Ellery, A., Kreisel, J. and Sommer, B., "The case for robotic on-orbit servicing of spacecraft: Spacecraft reliability is a myth", Acta Astronautica, vol. 63, 2008.

[4] Yasaka, T. and Ashford, W., "GSV: An Approach Toward Space System Servicing", Earth Space Review, Vol. 5, No. 2, 1996.

[5] Cougnet, C., Gerber, B., Heemskerk, C., Kapellos, K. and Visentin, G., "On-Orbit Servicing System of a GEO Satellite Fleet", In Proc. 9th ESA Workshop on Advanced Space Technologies for Robotics and Automation 'ASTRA 2006', ESTEC, Noordwijk, The Netherlands, 2006.

[6] Rebele, B., Krenn, R. and Schäfer, B., "Grasping Strategies and Dynamic Aspects in Satellite Capturing by Robotic Manipulator", In Proc. 7th ESA Workshop on Advanced Space Technologies for Robotics and Automation (ASTRA 2002), ESTEC, Noordwijk, The Netherlands, 2002.

[7] Wormnes K., de Jong J.H., Krag H. and Visentin G., "Throw-nets and tethers for robust space debris capture", In 64th International Astronautical Congress, IAC-13, A6.5, 2x16445, Beijing, China, 2013.

[8] Aslanov V. and Yudintsev Y., "Dynamics of large space debris removal using tethered space tug", Acta Astronautica 91(2013)149–156.

[9] Benvenuto R., Lavagna M., Cingoli A., Yabar C., and Casasco M., "MUST: Multi-body dynamics simulation tool to support the GNC design for active debris removal with flexible elements", in GNC 2014: 9th International ESA Conference on Guidance, Navigation & Control Systems, Porto, Portugal, 2014.

[10] Benvenuto R., Salvi S. and Lavagna M., "Dynamics analysis and GNC design of flexible systems for space debris active removal", Acta Astronautica 2015.

[11] Benvenuto R., Salvi S. and Lavagna M.: "Net capturing of tumbling space debris: contact modelling effects on the evolution of the disposal dynamics", In Proc. of 13th ESA Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA 2015), ESTEC, Noordwijk, The Netherlands, 2015.

[12] Rocchi A. and Lavagna M.: "Versatile electro-dynamic tethers dynamics simulator for debris mitigation tools design", In Proc. of 13th ESA Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA 2015), ESTEC, Noordwijk, The Netherlands, 2015.

[13] Wood G. and Kennedy D., "Simulating Mechanical Systems in Simulink with SimMechanics", Technical report, The MathWorks,
Inc., Natick, USA, 2003.

[14] Chudnovsky V., "Modeling Flexible Bodies in SimMechanics and Simulink", *Matlab Digest*, May 2006.

[15] V. S. Aslanov and A. S. Ledkov, "Dynamics of tethered satellite systems", Oxford, Woodhead, 2012.

[16] Leamy M.J., Noor A.K. and Wasfy T.M., "Dynamic simulation of a tethered satellite system using finite elements and fuzzy sets". Comput. Methods Appl. Mech. Eng. 190(37–38), 4847–4870, 2001.

[17] Williams P., "Dynamic multi-body modeling for tethered space elevators". *Delft University of Technology*, March 2009.

[18] Modi V.J., Pradhan S. and Misra, A.K., "Controlled dynamics of flexible orbiting tethered systems: analysis and experiments", J. Vib. Control 3(4), 459–497, 1997.

[19] Aslanov V.S. and Yudintsev V., "Dyamics of Large Debris Connected to Space Tug by a Tether", Journal of Guidance, Control, and Dynamics Vol. 36, No. 6, November–December 2013.

[20] Jasper L., Schaub H., Seubert C., Valery T. and Yutkin E., "Tethered tug for large low earth orbit debris removal", In Proc. of the AAS/AIAA Astrodynamics Specialists Conference (AAS12-252), Charleston, SC, 2012.

[21] Jasper L. and Schaub H., "Input shaped large thrust maneuver with a tethered debris object", In 6th European Conference on Space Debris, ESOC, Darmstadt, Germany, April 2013. Url: http://Hanspeterschaub.info/papers/jasper2013.pdf.

[22] Jasper L. and Schaub H., "Discretized input shaping for a large thrust tethered debris object", AAS/AIAA Space Flight Mechanics Meeting, Santa Fe, NM, January 26 - 30, 2014.

[23] da Cruz Pacheco G. F., Carpentier B. and Petit N., "De-orbiting of space debris by means of a towing cable and a single thruster spaceship: whiplash and tail wagging effects", in Proc. of Sixth European Conference on Space Debris, Darmstadt, Germany, April 22 – 25, 2013.

[24] Benvenuto R. and Lavagna M., "Towing tethers to control debris removal dynamics", in Proc. Of 65th International Astronautical Congress (IAC 2014), Toronto, Canada (2014).

[25] Astrium, "Robotic Geostationary Orbit Restorer (ROGER) Phase A final report", ROGSIBRE-FP Issue 1, 26 June 2003.

[26] Biesbroek R. et al., "The e.Deorbit study CDF study: A design study for the safe removal of a large space debris", 6th IAASS Conference, Montréal, Canada, 22/05/2013.

[27] Huang P., Zhang F., Ma J., Meng Z. and Liu Z., "Dynamics and configuration control of the Maneuvering-Net Space Robot System", Advances in space research 55 (2015) 1004–1014, 2015.

[28] Medina A., Cercos L., Stefanescu R., Benvenuto R., Lavagna M., Gonzales I., Rodriguez N. and Wormnes K., "Capturing Nets for Active Debris Removal: a Follow-Up on Microgravity Experiment Design to Validate Flexible Dynamic Models", In Proc. of 13th ESA Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA 2015), ESTEC, Noordwijk, The Netherlands, 2015.

[29] Wie B., Weiss H. and Arapostathis A., "Quaternion feedback regulator for spacecraft eigenaxis rotations", J. Guidance, Control and Dynamics, vol. 12, no. 3, pp. 375-380, May/June 1989.

[30] Singer N.C. and Seering W.P., "Preshaping command inputs to reduce system vibration, J. Dyn. Meas. Control 112, pp. 76–82, 1990.

[31] Xie X., Huang J., Liang Z., "Vibration reduction for flexible systems by command smoothing", J. Mechanical Systems and Signal Processing 39, 461–470, 2013.

[32] Seweryn K., Banaszkiewicz M., Maediger B., Rybus T. and Sommer J., "Dynamics of space robotic arm during interactions with non−cooperative objects", 11th Symposium on Advanced Space Technologies in Robotic and Automation, ESA/ESTEC, ESA/ESTEC, Noordwijk, The Netherlands, 12–14 April 2011.

[33] Nishida S. and Yoshikawa T., "Capture and Motion Braking of Space Debris by a Space Robot", International Conference on Control, Automation and Systems, Seoul, Korea, Oct. 17-20, 2007.

[34] Oda M., "Coordinated control of spacecraft attitude and its manipulator", in Proc. IEEE Conf. Robotics and Automation, pp. 732-738, Apr. 1996.

[35] Fernandes C., Gurvits L. and Li Z.X., "Attitude control of space platform/manipulator system using internal motion," in Space Robotics: Dynamics and Control, pp. 131-163, 1993.