Trajectory generation method for robotic free-floating capture of a non- cooperative, tumbling target

Marko Jankovic and Frank Kirchner

Abstract The paper illustrates a trajectory generation method for a free-floating robot to capture a non-cooperative, tumbling target. The goal of the method is to generate an optimal trajectory for the manipulator to approach a non-cooperative target while minimizing the overall angular momentum of the entire system (chaser plus target). The method is formulated as an optimal control problem (OCP) and solved via an orthogonal collocation method that transforms the OCP into a nonlinear programming problem (NLP). This way the dynamical coupling between the base and manipulator is actively used to reach the optimum capturing conditions. No synchronization of the relative motion between the target and chaser is necessary prior to the maneuver. Therefore, there is an inherent propellant advantage of the method when compared with the standard ones. The method is applied in 2D simulation using representative targets, such as a Vega 3rd stage rocket body, in a flat spin. The results of simulations prove that the developed method could to be a viable alternative or a complement to existing free-flying methods, within the mechanical limitations of the considered space manipulator. The study of the capture and stabilization phases was outside the scope of the present paper and represents future work that needs to be performed to analyze the operational applicability of the developed method.

Key words: Space debris, active debris removal, space robotics, free-floating trajectory generation, capture of non-cooperative target, optimal control, nonlinear programming.

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1 Introduction

Recent studies of the space debris population in Low Earth Orbit (LEO) have concluded that its certain regions have reached a critical density of objects, which will eventually lead to a cascading process called the *Kessler syndrome* [13]. Thus, there is a consensus among researchers that the active debris removal (ADR) should be performed in the near future if we are to preserve the space environment for future generations [13]. Among the proposed ADR capture technologies, those involving orbital robotics are at the moment the most mature ones since they have been successfully tested in-orbit in more than one occasion. Moreover, these technologies are among the most versatile ones given the high number of degrees of freedom they can generally control. Furthermore, once developed they can easily be re-purposed for other in-orbit tasks, such as the on-orbit servicing. However, robotic based solutions have been until today confined only to objects with very low level of non-cooperativeness (i. e. low attitude rates). Moreover, no robotic spacecraft has ever performed a capture of a non-cooperative, tumbling object[1], especially in the free-floating mode. The former mode is here defined as a control mode of a space robot during which the attitude control system (ACS) of the base spacecraft is non-active during the operation of the manipulator as opposed to the free-flying mode during which the ACS actively counteracts the motion of the base spacecraft due to the operation of the manipulator. The free-floating mode is especially interesting for robotic multi-target ADR missions or on-orbit servicing since it would lead to fuel savings and therefore extension of the overall duration of missions.

Grasping a target that has a residual angular momentum without considering it in the approach phase could pose difficulties to the ACS in the capture and post-capture phases phases of a mission and most probably would result in a failed maneuver [5, 6]. In fact, the actual capture phase involves physical contact between two bodies and transfer of forces and momenta. For as long as the capturing is not completed, these contact forces will have a random character. Therefore, it is advisable to have a a free-floating spacecraft during the maneuver to avoid random effects triggering the activation of an ACS that would lead to shocks and damage of the spacecraft and target [9]. Furthermore, in the post-capture phase the system will need to accommodate a wide variety of angular momenta, therefore requiring heavier reaction wheels and high powered actuators. This directly influences the total spacecraft mass and power consumption which is generally to be avoided. To overcome these limitations, the robotic control subsystem should be developed in such a way that is capable of performing the capture maneuver autonomously, taking into consideration its free-floating dynamics, as well as the angular momentum of the target object during the approach phase of the manipulator.

In this context, the following paper illustrates a method for trajectory generation of the approach phase of a spacecraft mounted manipulator that takes the advantage of the its free-floating dynamics to facilitate the capture of a non-cooperative, tumbling target. This is done by pre-loading a desired angular momentum onto the

[1] To best of our knowledge.

base spacecraft and using the manipulator to transfer it from the base to the arm itself. The method is formulated as an optimal control problem (OCP) and solved as a nonlinear programming problem (NLP).

The structure of the remainder of the paper is as follows: Sec. 2 is dedicated to a brief literature survey where major differences of the existing methods are pointed out with respect to (w. r. t.) the developed method. In Sec. 3 the trajectory generation method is defined by introducing the main notation, equations of motion, objectives and assumptions of the method. Sec. 4 presents the implementation of the method as an OCP. In Sec. 5 the results of numerical simulations are illustrated, considering representative targets, such as a Vega 3rd stage rocket body, in a flat spin. Finally, Sec. 6 provides the concluding remarks of the paper and envisioned future work that will improve the developed method.

2 State-of-the-Art

The capture of a target by means of a manipulator mounted on a spacecraft is a well known problem dating back to the early ’80s. Since then there has been a great variety of fundamental research performed on this topic. However, most of the times the dynamical coupling between the manipulator and its base has been regarded as a disturbance to be suppressed by either actively controlling the base, by means of an ACS [1, 2], or passively, by means of an optimized path of the manipulator [8] in order to maintain a fixed attitude of the base spacecraft in the inertial system for communication purposes. Furthermore, the stabilization and detumbling of the compound, once the target was captured, has been, most of the times, relegated entirely to an ACS of the base spacecraft [2, 12]. This could lead to a failed maneuver if a high angular momentum of the target is considered due to the limitations of an ACS, such as the amount of propellant or dimensions of reaction wheels (RWs).

More specifically, in [5], Dimitrov, D. et al., describe a trajectory generation method formulated as an NLP which facilitates the post-capture maneuver by preloading an angular momentum in the RWs of the ACS and using the manipulator to transfer it from the base to the manipulator. However, the authors focus mainly on minimizing the attitude disturbance of the base during maneuvers and assume an active ACS through the contact phase, which might lead to unexpected behavior of the overall system as evidenced in [9]. Furthermore, while they do minimize the angular momentum to be transferred to the base, they do not deal with the management of the angular momentum of the overall system (i. e. chaser plus target) relegating this task to the RWs and thus ACS of the base which might be a problem in case of angular velocities of targets higher then those considered by the authors, i. e. $> \pm 1\ {}^{\mathrm{deg}}\!/\!_{\mathrm{s}}$.

In [12], Lampariello, R. et al., on the other hand, describe a motion planning for the on-orbit grasping of a non-cooperative target. The motion planning includes the whole capture maneuver (i. e. from approach to the stabilization) for typical target tumbling motions, i. e. flat spin of $\pm 4\,\mathrm{deg/s}$. The method is formulated as an OCP and solved as an NLP. The collision avoidance is included in the method as an inequality constraint. However, the angular momentum management of the stack is relegated entirely to the ACS of the base spacecraft during the post-capture phase. The approach of the manipulator is performed in the free-floating mode and considered cost functions include the mechanical energy of the manipulator which allows reduced joint torques and velocities of the manipulator.

In [8], Flores-Abad et al., consider the capture of a tumbling target as an OCP trying to minimize joint torques and the attitude disturbance of the base spacecraft during the contact phase. This is done by directing the contact force through the center of mass of the compound. However, the method formulated in this way is found hard to be accomplished, due to the generally unpredictable contact dynamics. Moreover, management of the angular momentum of the target has not been addressed and the collision avoidance has not been mentioned. Furthermore, only a 2 degrees of freedom (DOF) manipulator is considered in the study.

In [1, 2], Aghilli, F., addressed the capture of a tumbling target as an OCP of the pre- and post-capture phases of a space robot. In the pre-grasping phase, an optimal trajectory is planned to intercept a grasping point on the target with zero relative velocity, subject to acceleration limit and adequate target alignment. In the post-grasping phase, the manipulator is used to damp out the angular and linear momenta of a target as quickly as possible subject to the constraints of the manipulator. However, both phases are performed in the free-flying mode, thus assuming usage of a coordinated control between the ACS and the manipulator. Moreover, the collision avoidance problem was not tackled in these studies.

The method presented in this paper builds upon the mentioned studies and tries to solve their issues. Mainly, the method is based on the Bias Momentum Approach (BMA) developed by Dimitrov D. et al. in [5]. However, with respect to the mentioned method, the novelty of the following work consists mainly in: (a) free-floating mode of the chaser (i. e., the ACS is completely switched-off during the approach maneuver), (b) limited kinetic energy of the chaser system at the end of the maneuver, (c) management of the overall angular momentum of the stack, (d) collision avoidance. This way, a spacecraft mounted robot would be able to capture a non-cooperative, tumbling target without the need to synchronize the relative attitude motion and with limited need to de-tumble the stack after the capture.

3 Method Definition

The capture of a tumbling target may be described essentially in four phases as illustrated in Fig. 1:

1. a chaser spacecraft performs the observation and pose[2] estimation of a target object,

[2] Defined as position and orientation of an object.

2. a chaser approaches a target using its ACS to place the target in a predefined berthing box,
3. the manipulator of the spacecraft approaches the designated berthing feature in either free-flying or free-floating mode,
4. the end-effector of the manipulator captures the berthing feature and the relative motion between the two objects is stabilized.

In case of angular speeds of a target higher then 5 $^{\mathrm{deg}}/_{\mathrm{s}}$, the current doctrine [3, 4, 15] dictates a synchronization maneuver that should precede the mentioned phases in order to match the relative attitudes of the robotic chaser spacecraft and tumbling target. However, this maneuver requires non negligible fuel requirements[3] which is why it should be minimized as much as possible especially in case of multi-target ADR or on-orbit servicing (OOS) missions, where the spacecraft would need to capture or service multiple targets during one mission. Thus, the method described in this paper aims at minimizing this requirement by exploring the possibility of generating an optimal trajectory of the manipulator to approach a target that would reduce the need for the follow-up de-tumbling phase. This phase is illustrated in Fig. 1c. It ends with the manipulator able to make the contact with a berthing feature of the target. It is assumed that only one useful berthing feature on the target exist and that it is pre-selected by a user beforehand for simplicity.

3.1 Equations of Motion and Main Notation

The dynamics of a generic rigid free-floating manipulator composed of a free-floating base and an $m-$link serial manipulator with no external forces/moments acting on the spacecraft, can be expressed as follows [21]:

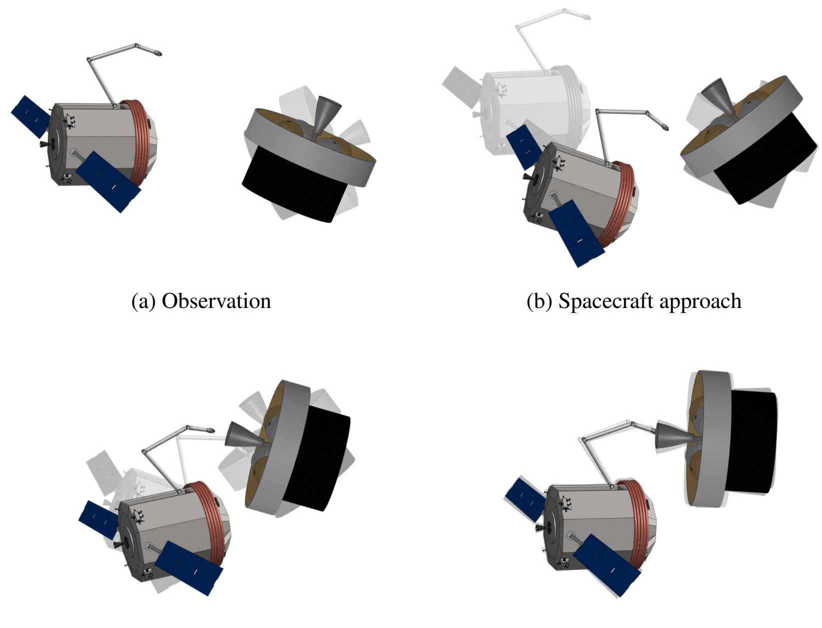
$$\begin{bmatrix} H_b & H_{bm} \\ H_{bm}^{\top} & H_m \end{bmatrix} \begin{bmatrix} \ddot{x}_b \\ \ddot{\phi}_m \end{bmatrix} + \begin{bmatrix} c_b \\ c_m \end{bmatrix} = \begin{bmatrix} 0 \\ \tau \end{bmatrix} \tag{1}$$

where x_b expresses the pose of the base spacecraft, ϕ_m are the joint angles of the manipulator and τ are the joint torques. H_b, H_m and H_{bm} are the inertia matrices of the base body, manipulator and the coupling between the base and arm, respectively. c_b and c_m are the velocity dependent non-linear terms of the base and arm, respectively [21].

All the variables are expressed w. r. t. an inertial reference frame, Σ_I, assumed to be moving in an orbital plane of the space robot and thus translating with it for the short duration of the capture maneuver [21].

Integrating the upper part of Eq. 1 w. r. t. time it is possible to obtain the equation of the total momentum of the free-floating system around the center of mass (COM) of the base spacecraft as [21]:

[3] Especially considering that during one capture it will need to be performed twice, once to synchronize the motion and the second time to de-tumble the chaser-target stack.



(a) Observation (b) Spacecraft approach

(c) Manipulator approach (d) Capture and stabilization

Fig. 1: Mission phases of a robotic capturing of a non-cooperative target.

$$\mathscr{L} = \begin{bmatrix} P \\ L \end{bmatrix} = H_b \dot{x}_b + H_{bm} \dot{\phi}_m \tag{2}$$

where P and L are the linear and angular momenta of the robotic system around the center of mass of the base.

Alternatively, the total momentum equation can be re-written w. r. t. Σ_I as [5]:

$$\begin{bmatrix} P \\ L \end{bmatrix} = H_b \dot{x}_b + H_{bm} \dot{\phi}_m + \begin{bmatrix} 0 \\ r_b \times P \end{bmatrix} \tag{3}$$

where P and L are the linear and angular momenta of the robotic system around the inertial reference frame, Σ_I.

Therefore, the angular momentum equation can be expressed in a shorter form as [5]:

$$L = \tilde{H}_b \omega_b + \tilde{H}_{bm} \dot{\phi}_m + r_g \times P \tag{4}$$

where $\tilde{H}_b$ and $\tilde{H}_{bm}$ are the modified inertia matrices as defined in [5, 20] and r_g is the vector from Σ_I to the COM of the whole system.

Alternatively, Eq. 4 can be written in even a shorter form as [5]:

$$L = L_b + L_{bm} + L_p \tag{5}$$

where the individual contributions to the overall angular momentum of the space robot, by the partial angular momenta of the base, L_b, robot, L_{bm} and linear momentum, L_p, are clearly evidenced and give us some insight on how the overall angular momentum of the space robot can be managed if no external forces are applied to the centroid of the system. In fact, Eqs. 4 and 5 express the first order non-holonomic constraint of a free-floating robot [21] which couples the motion of the manipulator and its base spacecraft. Therefore, assuming no external forces applied to the system and no linear motion of the center of mass of the overall system, i. e. $L_p = 0$, it is evident from Eq. 4 that because of the conservation of momentum any movement of the manipulator will only results in a redistribution of the already present angular momentum in the system. Thus, if we are to optimize the distribution of the angular momentum of the system during the approach phase, where the ACS of the base spacecraft is switched off, the only way to achieve it would be by optimizing the motion of the manipulator, i. e. its joint angular velocities or more concretely the joint torques.

3.2 Method Objectives and Assumptions

The objective of the developed method is to provide an optimal approach strategy of the manipulator, based on a proper distribution of the angular momentum within the system, to facilitate the control of the manipulator and ACS in the post-capture phase and thus lower the overall propellant needs of the mission.

The assumptions made in this study are the following:

1. the target undergoes a constant flat spin motion, i. e. a pure rotational motion around its principal axis of inertia, assumed to be known in advance and being $\geqslant 5\,{}^{\mathrm{deg}}/_{\mathrm{s}}$ in magnitude,
2. the inertial characteristics of the target are well known,
3. there are no external forces acting on the entire system (chaser plus target),
4. there is no relative linear motion between the bodies, at the beginning of the approach maneuver,
5. the system is composed only of rigid bodies,
6. the ACS of the chaser spacecraft is switched-off during the approach phase,
7. the manipulator is redundant with respect to the imposed task constraints,
8. the contact and de-tumbling phases are not considered at the moment by the optimization method.

With those assumptions in mind and referring to Eq. 5 and Fig. 2, the angular momentum of the entire system (chaser plus target) can be sufficiently defined by two variables: L (or better L_c), and L_t, representing the angular momentum of the chaser and target, respectively.

To facilitate the post-capture (i. e. the stabilization) phase of a capture mission, the management of the angular momentum of the entire system has to be taken into consideration during the approach phase. To this end, the developed method considers as the most favorable condition the following one: $L_c = L_b + L_{bm} = -L_t$. Should this condition be satisfied, no post-capture angular momentum management should be needed since the overall momentum of the system (chaser plus target), at the contact of the manipulator with the target, would be zero. To reach this condition while taking into consideration the made assumptions, $-L_t$ needs to be initially pre-loaded onto the base spacecraft by means of an ACS, prior to the manipulator maneuver and then re-distributed via the manipulator. The amount of momentum to be re-distributed from the base to the manipulator will depend on the desired pre-contact strategy, as outlined in [5]. In our case, we would like to off-load the base spacecraft as much as possible to minimize the transfer of angular momentum from the target to the base spacecraft in the post-capture phase of the mission. To reach such a state the following condition needs to be imposed onto the trajectory of the robotic system at the end time of an approach maneuver [5]:

$$\begin{cases} \left\| L_{bm}(t_f) \right\| \leq \| L_t \| \\ L_{bm}(t_f) \cdot L_t < 0 \end{cases} \tag{6}$$

The condition indicates that the optimal amount of angular momentum to be transferred onto the manipulator prior to a contact phase should be in any case smaller or equal in magnitude and opposite in direction to that of the target such that only a minimal residual angular momentum will be transferred to the base spacecraft after the contact phase. Ideally that condition would be:

$$\begin{cases} L_{bm}(t_f) = -L_t \\ L_b(t_f) = 0 \end{cases} \tag{7}$$

where the angular momentum initially pre-loaded onto the base is completely transferred to the manipulator. However, this might not always be possible due to mechanical limitations of manipulators which is why the condition expressed in Eq. 6 is the used and not the one expressed in Eq. 7.

4 Method Implementation

The trajectory generation method developed to optimize the distribution of partial angular momenta of the chaser spacecraft has been implemented as a constrained nonlinear optimization problem (OCP). The OCP has been transformed, via a direct collocation method, into a nonlinear programming problem (NLP) and solved using the MATLAB's optimization toolbox.

Given the complexity of the OCP at hand and the need for a good initial guess, the optimization is performed in two steps. At first a reasonable guess of the trajectory is obtained with: a simple objective function, limited number of collocation points and relaxed error tolerances. Then, the solution is refined using a more complex objective function, larger number of collocation points and smaller error tolerances.

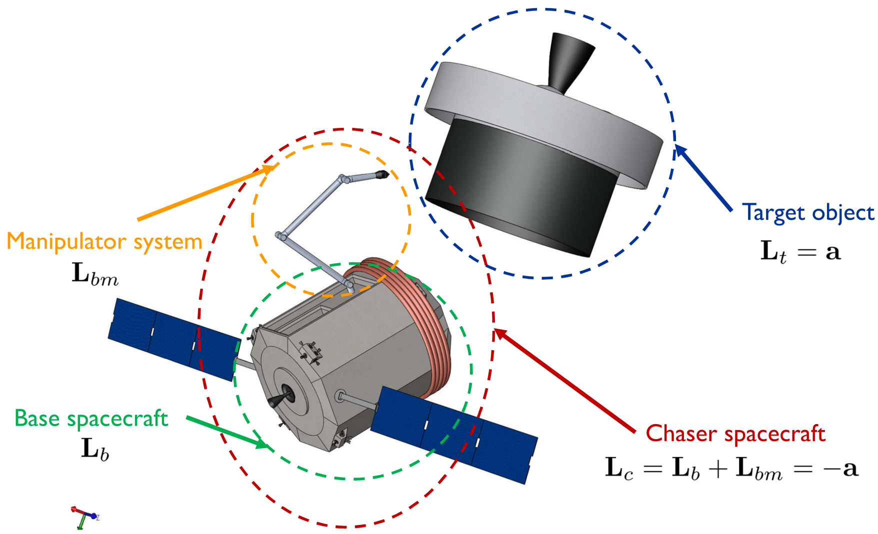


Fig. 2: Distribution of partial angular momenta of the system.

Morse specific information about the implementation of the method can be found in what follows.

4.1 Mathematical Formulation of the Optimization Problem

The optimization problem of the manipulator approach maneuver is formulated as a single-phase continuous-time trajectory optimization problem with an objective to minimize in the first step a path integral:

$$\min_{t_0,t_f,x(t),u(t)} \int (\tau^\top \tau) dt \tag{8}$$

where its minimization entails smaller joint torques during the maneuver. t_0 and t_f are the initial and final time of the approach phase, respectively; x are the state variables of the system (i. e. $x \triangleq [x_b; \phi_m; \dot{x}_b; \dot{\phi}_m]$) and u are the control variables of the system (i. e. $u \triangleq \tau$ joint torques).

In the second step the objective function has been expressed in Bolza from, thus containing both a boundary objective and a path integral. The objective function defined for this second step has the following expression:

$$\min_{t_0,t_f,x(t),u(t)} \kappa_1 (\sqrt{\omega_b^2(t_f)}) + \int_{t_0}^{t_f} \left[\kappa_2 (\dot{\phi}_m^T \dot{\phi}_m) + \kappa_3 (\tau^\top \tau) \right] d\tau \tag{9}$$

where the Mayer term of the objective function, i. e. the boundary objective, expresses the magnitude of the angular velocity of the base, ω_b, at t_f and the Lagrange term of the objective function, i. e. the path integral, is a sum of the squared values of joint velocities and joint torques. κ_1, κ_2 and κ_3 represent the weights of individual terms of the objective function and are custom to each problem.

The minimization of the Mayer term is meant to contain the magnitude of the angular velocity of the base to achieve a desired distribution of partial momenta of the robot (as described in Eq. 6), while the minimization of the Lagrangian term should contain the angular velocities of the joints. The torque squared term represents only a regularization term of the objective function, as suggested in [10].

Both objective functions are subject to:

- the free-floating dynamics of a space robot (see Eq. 1);
- kinematics constraints:

$$\begin{gathered} x_h(t_f) - x_t(t_f) = 0 \\ \dot{x}_h(t_f) - \dot{x}_t(t_f) = 0 \end{gathered} \tag{10}$$

which define the final pose and velocities of the end-effector of the manipulator, i. e. x_h and $\dot{x}_h$, respectively;

- state, control, time and collision avoidance constraints:

$$\begin{gathered} \phi_m^- \leq \phi_m(t) \leq \phi_m^+ \\ \dot{\phi}_m^- \leq \dot{\phi}_m(t) \leq \dot{\phi}_m^+ \\ \tau^- \leq \tau \leq \tau^+ \\ t^- \leq t_0 < t_f \leq t^+ \\ r_{coll}(\phi_m(t)) \leq 0 \end{gathered} \tag{11}$$

where r_{coll} represents the collision avoidance constrains;

- initial and final bounds:

$$\begin{gathered} x_b(t_0) = 0 \\ \phi_m(t_0) = \phi_{m0} \\ \dot{\phi}_m(t_0) = 0 \\ \dot{x}_b(t_0) = -H_b^{-1} M_t \dot{x}_t \\ t_o = 0 \\ 0 \leq t_f \leq 60 \end{gathered} \tag{12}$$

where M_t is the mass matrix of the target as defined in [16] and x_t is the pose of the target object. The expression $\dot{x}_b(t_0) = -H_b^{-1} M_t \dot{x}_t$ reflects the desired initial conditions, defined in Subsec. 3.2 on page 7, i. e. $L_c(t_0) = L_b(t_0) = -L_t$.

4.2 Implementation of the Optimization Problem

The described OCP has been implemented as an NLP using an open-source MATLAB library OptimTraj [11] designed for solving continuous-time, single-phase trajectory optimization problems. The library implements several direct collocation methods, such as the trapezoidal and Hermit-Simpson collocations, multiple shooting and orthogonal Chebyshev-Lobatto collocation[4]. The latter was chosen in this study as a collocation method of choice given its robustness and efficiency when compared to lower order collocation methods implemented in OptimTraj library.

The solution of an NLP was then found with the MATLAB's fmincon closed-source, solver which is part of the Optimization Toolbox.

The kinematics and dynamics of the free-floating platform were developed using the Recursive Dynamics Simulator (ReDySim)[17, 18] and SPAcecraft Robotics Toolkit (SPART) [19] MATLAB libraries.

The collision avoidance of bodies was implemented via the MATLAB function *distLinSeg* developed by Sluciak, O., using an algorithm for fast computation of the shortest distance between two line segments developed by Lumelsky, V. J. [14].

5 Method Evaluation

The trajectory generation method outlined in the previous section has been evaluated in 2D simulation studies performed with a 4 DOF manipulator whose mass properties were chosen to be similar to those of the robotic arm used in the Japanese ETS-VII robotic mission [21], as visible in Tab. 1.

The considered target objects were: a spacecraft (S/C), having similar physical characteristics to those of the robotic base spacecraft, and a Vega 3rd stage rocket body (R/B). The inertia tensor of the latter was approximated for simplicity to that of a cylinder having: a mass, diameter and length of: ~1000 kg[5], 1.907 m and 3.467 m, respectively. The inertia tensor of the target S/C on the other hand was calculated considering a cube having an edge length of 2 m and a mass of 868.92 kg. More details can be found in Tab. 1.

Table 1: **Inertial parameters of the chaser and targets**

Body	Mass [kg]	I_{zz} [$\mathrm{kg \cdot m^2}$]
Link 1	57.46	0.2281
Link 2	38.43	0.1525
Link 3	26	0.1032
Link 4	18.49	0.0734
Base S/C	868.92	579.28
Generic target S/C	868.92	579.28
Vega 3rd stage R/B	999.6	1228.47

For the purposes of simulation, the targets were assumed to be in a flat-spin attitude motion around their principal axis of inertia (i. e. z axis in simulations) with a constant rate of $-5\,\mathrm{deg}/\mathrm{s}$.

[4] Implemented in the library using an additional open-source MATLAB library Chebfun [7].

[5] 833 kg + 20 % of margin.

The initial configuration of the robot was assumed in all simulations to be the following:

$$\begin{array}{rl} x_b(t_0) = 0_{3\times 1} & (\mathrm{m}, \mathrm{deg}) \\ \phi_m(t_0) = [-60, 45, 45, -30]^T & (\mathrm{deg}) \\ \dot{\phi}_m(t_0) = 0_{4\times 1} & (\mathrm{deg}/\mathrm{s}) \\ \dot{x}_b(t_0) = -H_b^{-1} M_t \dot{x}_t & (\mathrm{m}/\mathrm{s}, \mathrm{deg}) \end{array} \tag{13}$$

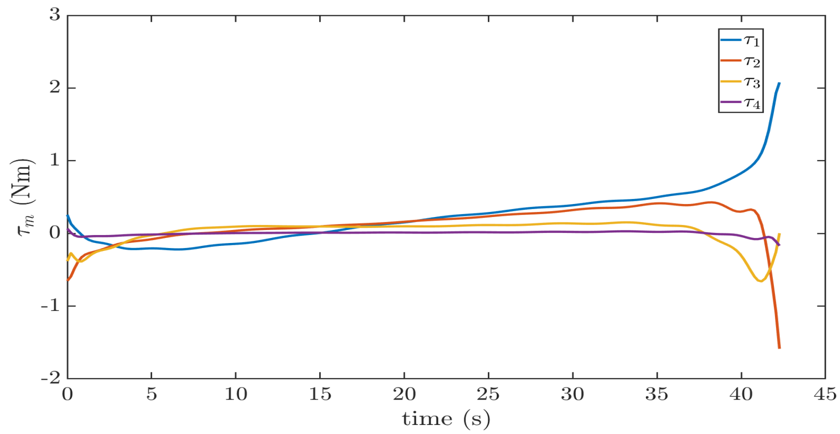
The grasping features/points on the targets were assumed to be the nozzles of their main propulsion systems, placed at a distance of 0.6 m and 0.9 m from the main bodies of the S/C and Vega 3rd stage R/B, respectively. Their inertial 2D position was therefore assumed to be at $r_{gf} = [0.3149, 3.6615]^T$ meters. The initial position of the centroid of the base spacecraft was instead assumed to be at the origin of the inertial frame, Σ_I, therefore at $r_b = [0, 0]^T$ meters.

The results of the conducted simulation studies, based on the previous constraints and conditions, are presented in Figs 3 and 4. The optimized trajectories were obtained using 30 collocation points and objective function weights $\kappa_1 = 1$, $\kappa_2 = 0.02$, $\kappa_3 = 0.001$. In all studies, the initial guess of a trajectory was always generated with a lower-order, trapezoidal collocation method, in order to find a first coarse solution to an easy to solve problem, thus reducing the amount of computational effort needed for the overall optimization.

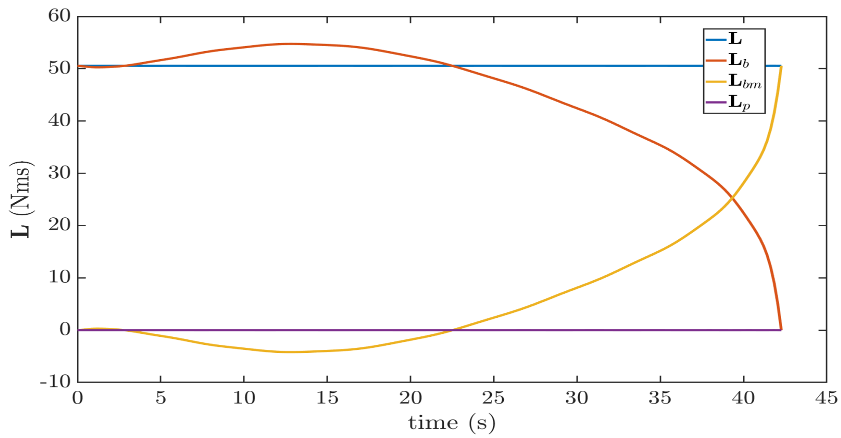
From the results it can be concluded that, with the developed method it is possible to obtain a locally optimal approach trajectory of a free-floating space robot to capture a tumbling target under the imposed assumptions and conditions. Specifically, in case of a target having mass properties similar to those of the chaser base S/C, an ideal momentum distribution, as expressed in Eq. 7, is possible, as visible in Fig. 3b. This condition assures that no angular momentum will be transferred through the manipulator to the base during a contact phase. Therefore, the post-capture manipulator and ACS control would be significantly simplified since the overall capture operation could be ideally achieved simply by servo locking the manipulator joints.

In case of a target with bigger inertial properties and/or higher angular velocity, only partial momentum distribution transfer is achievable, as visible in Fig. 4b. This distribution would cause the remaining angular momentum, resulting from the difference between the target angular momentum and that of the manipulator, i. e. $L_t - L_{bm}$, to transfer to the base through the manipulator, with a transfer rate depending on a variety of conditions, such as the pre-contact configuration of the manipulator, contact forces, post-capture control, etc.. Therefore, the post-capture manipulator control and the overall capture procedure would be more complex with respect to the ideal case. Nevertheless, this is not found to be a major drawback of the implemented method since it could be overcome by either changing the mass ratio between the base S/C and manipulator or by using this method in combination with more standard free-flying methods where only a residual angular velocity of a target would be compensated with the developed method.

The fuel requirements (i. e. the required change in velocity or Δv) of the proposed method were found to amount to $\Delta v = 0.1\,\mathrm{m}/\mathrm{s}$, which is four times less then that of a



(a) Joint torques of the manipulator

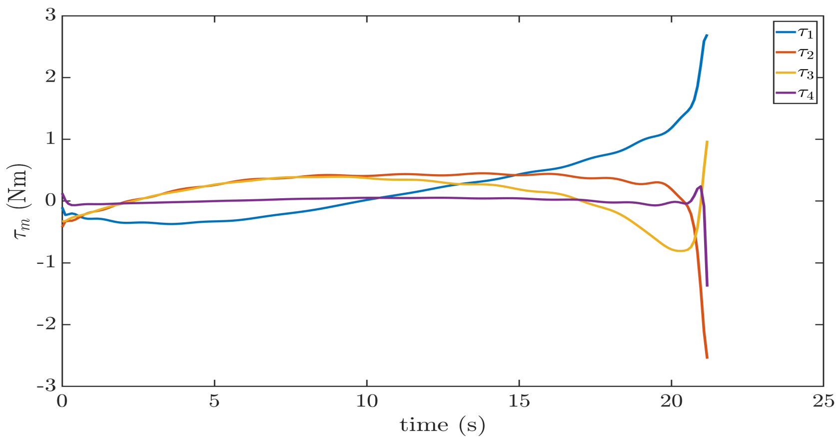


(b) Angular momenta of the chaser S/C

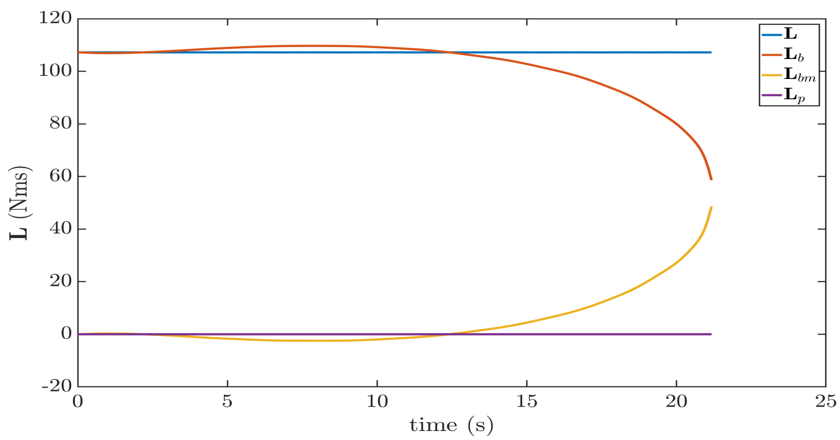
Fig. 3: Approach trajectories of joint torques and angular momenta of the robot for a generic S/C target having $\omega_t = -5\,{}^{\mathrm{deg}}/_{\mathrm{s}}$

standard syncing maneuver requiring $\Delta v = 0.4016\,{}^{\mathrm{m}}/_{\mathrm{s}}$, for the maneuver performed at the same distance of the grasping feature from the COM of the chaser S/C.

Based on the previous results it is possible to asses that the advantages of the method are the: (a) minimum angular motion of the compound after the capture (w. r. t. the inertial reference frame), (b) minimum redistribution of L_t within the chaser upon the contact, thus implying easier post-capture manipulator and ACS control, (d) no need for an ACS during the approach and post-capture phases of the manipulator. The disadvantages of the current implementation of the method are on the other hand assessed to be: (a) inability to transfer very high magnitudes of L_b or better of L_t onto the manipulator, (b) need for a pre-loaded angular momentum onto



(a) Joint torques of the manipulator



(b) Angular momenta of the chaser S/C

Fig. 4: Approach trajectories of joint torques and angular momenta of the robot for a Vega rocket body target having $\omega_t = -5\,\mathrm{deg}/\mathrm{s}$

the base S/C, (c) nonexistence of tracking phase that would permit uncertainties in the position of the grasping feature.

6 Conclusions

A method for the trajectory generation of the approach phase of a robotic ADR or OOS mission has been described. The method has been formulated as an OCP from the point of view of redistribution of the angular momentum between the manipulator and its base spacecraft. The objective of the optimization is to limit the transfer of the angular momentum from the target to the base spacecraft at the time of contact. The method allows to deal with tumbling targets without the need for relative synchronization and usage of the ACS during the de-tumbling phases. The method has proven to be a viable option to more traditional methods since: it would allow an easier post-capture/stabilization control of the manipulator and base S/C and introduce fuel savings especially in case of multi-target ADR or OOS missions. Nevertheless, the current implementation of the method presents some limitations that will need to be tackled in the near future to prove its operational applicability in a real-world scenario. Those limitations include the nonexistence of a tracking phase during the manipulator approach and lack of analysis of the impact of the developed method onto the subsequent capture and stabilization phases.

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