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On the Capture of Tumbling Satellite by a Space Robot

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***Abstract*— This paper deals with problems related to the capture of a tumbling satellite by a space robot. The minimization of the base attitude deviation before and after the contact with the target is discussed from the viewpoint of angular momentum distribution. By using the bias momentum approach during the approaching phase, impedance control during the impact, and distributed momentum control during the post-impact phase, we propose a possible control sequence for the successful completion of a capturing operation.**

I. Introduction

In recent years, the capture of a free-floating target in orbit has been recognized as a priority task. Its importance is apparent from the fact that in most cases capturing operation should precede missions like servicing, inspection and assembly which are critical for the survival of existing satellites in orbit.

There has been a great deal of fundamental research in the area of space robotics and though capturing a tumbling object in space is a well known problem, it is difficult to distinguish one of the solutions proposed up to now, which can solve it readily. Discussing the whole process from the trajectory planning to the post-impact control is an arduous task. The nature of the problems occurring in the different phases of the capture can be completely different so most of the researchers tend to separate the operation into closing in maneuver, approach[1], impact and post-impact motion.

A. Brief literature review

Most of the solutions presented up to now are from the viewpoint of force impulse generated during the contact. Different strategies for its estimation and minimization are presented in [1], [2], [3]. The concept of joint resistance model was introduced in [4], furthermore, the authors proposed the so called *impulse index* and *impulse ellipsoid* which adequately describe the force impulse characteristics. The effect of a "payload impact" on the dynamics of a flexible-link space robot is discussed in [5]. The application of impedance control when capturing a non-cooperative target is proposed in [6]. The condition which guarantees that the target will not be pushed away after the contact is clarified. A comprehensive discussion about the usage of the "*reaction null space*" is made in [7], [8]. The authors utilize the null space of the coupling

[1]Here, with *approach*, the approaching motion of a manipulator arm to a target satellite is implied.

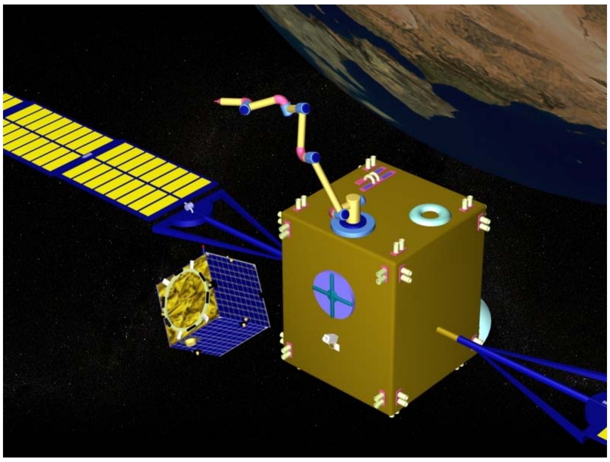

Fig. 1. Chaser and target satellites.

inertia matrix in order to decouple the base and manipulator dynamics. Furthermore, they showed that obtaining joint velocities using this approach does not influence the momentum distribution whatsoever.

Other possible solutions to the capturing problem can be derived from the viewpoint of the angular momentum of the target object. Grasping a target satellite without considering its momentum will impose difficulties for the post-impact control and most probably the capturing operation will fail. Different solutions are proposed up to now. One of them utilizes a device with controllable momentum wheels ("space leech"), which has to be attached to the target and absorb the angular momentum [9]. In [10], the idea of rotational motion-damper is proposed. Using a *contact/push* based method, the angular momentum from the target is transferred to the chaser satellite in portions. This could result however, in separation from the target after each contact and therefore, the usage of gas-jet thrusters for the compensation of the chaser satellite's linear motion might be necessary. This method is useful if the tumbling rate of the target is very large and direct capture is not possible. A similar method using "impulsive control" is proposed by Yoshikawa et al. [11]. A verification of the above strategy using experiment, is reported in [12]. In [13], Nakamura et al. utilize a "tethered retriever" which is guided to the target through the tension force in the tether and thrusters positioned on the retriever. During the post-impact phase, the angular momentum of the target is "absorbed" in attitude devices positioned on the retriever. In [14], the chaser satellite makes a fly-around maneuver in such a way that the capturing operation can be conducted with small relative motion between the two systems. The authors propose a "free motion path method," which enables us to completely ignore the non-linearity effect in the dynamics by taking advantage of the conservative quantities of the system. In [15] using an extended Kalman filter, estimation of the target's motion is made. The authors assume that the inertia parameters of the target are known or can be estimated. At a next step the centroid of the chaser satellite is repositioned (using thruster power) to be along the angular momentum vector of the target satellite, and the spacecraft is actuated in order to obtain a certain angular velocity which can facilitate the manipulator approaching motion. In addition, experimental results are presented.

Other references include studies related to planning safe kinematic trajectories during the closing in maneuver to a target object [16], [17]. Some control aspects of a capturing operation are studied in [18], [19], [20], [21]. The path planing problem to a free-floating target for a manipulator with angular momentum is addressed in [22], [23]. The capture of a spinning object using a dual flexible arm manipulator is studied in [24]. A development of a laboratory simulator for motion study of free-floating robots in relation to a target object is reported in [25]. Using this laboratory simulator, design issues related to free-floating planar robotic systems in view of optimal chasing and capturing operation, are addressed in [26]. Utilization of two free flyers for capture and manipulation of an object in space is presented in [27]. Notes on dynamical modeling and control of spacecraft-mounted manipulators during a capturing operation are made in [28].

B. Problems that need to be considered

The discussion of the capturing problem of a tumbling target satellite is involved. Some of the problems that need to be considered can be outlined as follows; (i) estimation of the motion profile of the grasping point is necessary. When the inertia characteristics of the target are unknown, obtaining a long term estimation is challenging [30], [29], [31]; (ii) the planning algorithm has to design a feasible approaching trajectory, that minimizes the contact forces during the impact-phase, as well as the reactions transferred to the base during the manipulator approaching motion; (iii) if the approach is interrupted, reliable estimation should be performed again; (iv) during the post-impact phase the momentum initially stored in the target satellite, transfers to the chaser and imposes difficulties from the viewpoint of base attitude control. Furthermore, releasing the target satellite leads to collision risks with the manipulator links and spacecraft's base. Management of the momentum of the target has to be performed. If methods for such management are not examined before the approaching motion, the capturing operation could fail. As already mentioned, in [10], [11], [12] a strategy for such momentum management based on a *contact/push* based method is proposed. Such strategy is useful when the momentum stored in the target satellite is large, and direct capture is not possible. If *contact/push* based method is used, each contact with the target can be approximated as an impulsive force applied to the end-effector. In such case, planing of pre-impact arm configuration for minimization of the base reactions is advantageous [4], [7], [5], [3], [2]. It should be noted that, in the case of a tumbling target the magnitude and direction of the contact forces has to be assumed unknown and constantly changing, hence, a particular pre-impact manipulator configuration does not provide significant advantages. Furthermore, the management of the angular momentum of the tumbling target satellite during the post-impact phase leads to new requirements towards the control strategies to be utilized. The angular momentum, however, is a conservative quantity and does not depend on the internal wrenches (forces and moments) in the system. Note, that the contact forces/torques are internal from the viewpoint of the entire system consisted of the chaser and target satellites. Therefore, planning of pre-impact arm configuration has to be replaced with planing of pre-impact momentum distribution as proposed in [32], [33].

C. The proposed solution

In this article we present a possible solution to some of the difficulties outlined above. We focus on minimizing the base attitude reactions during the approaching, impact and post-impact phases. It should be noted that, although it is tempting to use powerful gas/jet thrusters for this purpose, important insights are obtained from a familiarity with the "external-torque-free" motion of the entire system before, during and after the contact with the tumbling target satellite. Furthermore, reaction jet's fuel is nonrenewable and limited resource in space and should be used only when absolutely necessary.

The proposed capturing sequence is based on the utilization of three control strategies, namely: (i) *bias momentum approach* to be used during the approaching phase, in order to obtain a favorable pre-impact angular momentum distribution; *impedance control* during the impact, to guarantee that the target satellite will not be pushed away during the contact; (iii) *distributed momentum control* during the post-impact phase, that manages the momentum in the system in such a way that no base attitude change occurs.

II. Preliminaries and Main Notation

A. Basic equations

The behavior of a free-floating manipulator system can be fully described by the momentum conservation equation, which can be expressed in the following form:

$$\begin{bmatrix} \boldsymbol{P} \\ \boldsymbol{L} \end{bmatrix} = \boldsymbol{H}_b \begin{bmatrix} \boldsymbol{v}_b \\ \boldsymbol{\omega}_b \end{bmatrix} + \boldsymbol{H}_{bm}\dot{\boldsymbol{\phi}}_m + \boldsymbol{H}_{br}\dot{\boldsymbol{\phi}}_r + \begin{bmatrix} \boldsymbol{O} \\ \boldsymbol{r}_b \times \boldsymbol{P} \end{bmatrix} \quad (1)$$

where $\boldsymbol{P}$ and $\boldsymbol{L}$ are the linear and angular momenta of the system. We choose the linear and angular velocity of the base satellite $(\boldsymbol{v}_b, \boldsymbol{\omega}_b)$ and the motion rates of the manipulator joints and reaction wheels' rotation angles $(\dot{\boldsymbol{\phi}}_m, \dot{\boldsymbol{\phi}}_r)$ as generalized coordinates.

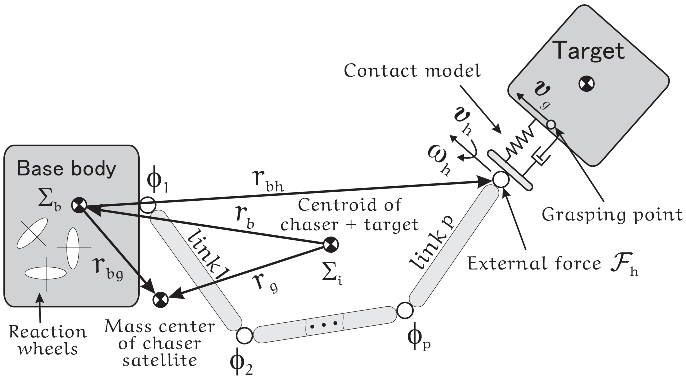

Fig. 2. Model of a n DOF space robot capturing a target.

The formulation is not limited to a single manipulator arm, however, for the derivations made in this paper we assume a serial manipulator with n degrees of freedom (DOF) and a system of three reaction wheels, mounted on a base body as shown in Fig. 2. Points of interest are Σ_i and Σ_b, which represent the origin of the inertial frame and the base centroid, respectively.

Matrices $\boldsymbol{H}_b$ and $\boldsymbol{H}_{br}$ are the inertia of the base and reaction wheels, respectively. $\boldsymbol{H}_{bm}$ is the coupling inertia matrix between the base and manipulator arm. In general, they are functions of the joint and base variables. However, in the absence of external wrenches, $\boldsymbol{H}_b$, $\boldsymbol{H}_{bm}$ and $\boldsymbol{H}_{br}$ will depend only on $\boldsymbol{\phi}_m$. Hence, the manipulator motion can be used in order to control the base motion profile, and in particular to keep it equal to zero. The derivation of equation (1) can be found in [34].

Next, we will state our assumptions and briefly overview some useful equations which are to be used as basis for further derivations.

B. Assumptions

In this study, a robotic manipulator mounted on a chaser satellite is assumed to capture a target object. We assume that;

$\boldsymbol{a_1}$) the target undergoes constant linear and angular motion and its angular momentum is known in advance (precise estimation is not necessary) [29], [30];

$\boldsymbol{a_2}$) there are no external forces acting on the entire system (chaser plus target). No gas-jet thrusters are used on the chaser's base. For attitude stabilization only reaction wheels are utilized;

$\boldsymbol{a_3}$) there is no relative linear motion between the mass centroids of the chaser and target;

$\boldsymbol{a_4}$) the inertial frame Σ_i is fixed in the center of mass of the entire system;

$\boldsymbol{a_5}$) the manipulator is redundant with respect to the base angular motion task;

$\boldsymbol{a_6}$) the capturing operation is successfully completed when the angular momentum from the target is transferred in the reaction wheels on the chaser satellite.

C. Angular momentum decomposition

During the impact and post-impact phases of a capturing operation momentum is "exchanged" between the chaser and target satellites. Especially the angular component of this momentum can be quite harmful. For a satellite-based chaser system, it can lead to attitude destabilization. When the robot is mounted on a flexible supporting structure, high amplitude vibrations will be induced. Taking into consideration the current assumptions, equation (1) can be reformulated with respect to the base attitude only. Eliminating the linear velocity of the base from the upper part of (1) results in a system of equations where $\boldsymbol{v}_b$ is implicitly accounted for.

$$\boldsymbol{L} = \tilde{\boldsymbol{H}}_b\boldsymbol{\omega}_b + \tilde{\boldsymbol{H}}_{bm}\dot{\boldsymbol{\phi}}_m + \tilde{\boldsymbol{H}}_{br}\dot{\boldsymbol{\phi}}_r + \boldsymbol{L}_p \tag{2}$$

where $\boldsymbol{L}_p = \boldsymbol{r}_{bg} \times \boldsymbol{P} + \boldsymbol{r}_b \times \boldsymbol{P} = \boldsymbol{r}_g \times \boldsymbol{P}$ (see Fig. 2). From assumptions ($\boldsymbol{a_2}$) and ($\boldsymbol{a_4}$) it follows that before the contact, the linear momentum of the chaser and target systems with respect to Σ_i will be zero, hence $\boldsymbol{L}_p = 0$. Each of the three remaining components on the right side of (2) defines a partial angular momentum of the system. The first term represents the angular momentum of the base body as a result of its attitude change, the second is related to the manipulator motion and is called the coupling angular momentum between the base and the manipulator [7]. The third term is the angular momentum in the reaction wheels.

$$\boldsymbol{L}_b = \tilde{\boldsymbol{H}}_b\boldsymbol{\omega}_b \;\; ; \;\; \boldsymbol{L}_{bm} = \tilde{\boldsymbol{H}}_{bm}\dot{\boldsymbol{\phi}}_m \;\; ; \;\; \boldsymbol{L}_r = \tilde{\boldsymbol{H}}_{br}\dot{\boldsymbol{\phi}}_r$$

By applying internal torques in the manipulator joints and reaction wheels, the three partial angular momenta can change in a desired way. We call this change momentum redistribution. In other words, though the amount of $\boldsymbol{L}$ present in the system is constant, its distribution over the base, manipulator and reaction wheels can vary. In the following section it will be shown that the momentum distribution before the contact with the target is closely related to the base attitude deviation after the contact. With a proper choice of the three partial angular momenta one can facilitate the post-impact attitude control. Furthermore, the process of angular momentum redistribution results in manipulator motion, which can be utilized in order to generate a feasible end-effector trajectory [34].

III. Approaching Phase

One of the main characteristics of a capturing operation in orbit is the momentum conservation if there are no external forces. If just the chaser or target system is considered, it might undergo momentum change, however, in the entire system the conservation law will hold. Under the present assumptions, during the approaching phase, the angular momentum in the entire system can be sufficiently defined by four variables, namely $\boldsymbol{L}_{bm}$, $\boldsymbol{L}_r$, $\boldsymbol{L}_b$, and the angular momentum of the target satellite $\boldsymbol{L}_t$. The amount of momentum stored in each of them plays an important role for the successful completion of the capturing operation. The zero attitude change restriction can be expressed as $\boldsymbol{L}_b = 0$. In Fig. 3 four typical distributions (immediately before the impact) are depicted. Next, a comparison among them will be made. In order to do so, it will be assumed that the manipulator joints are servo locked after the contact with the target, and a simple PD feedback attitude control via reaction wheels is utilized[2].

A. Non-bias distribution

The distribution depicted in Fig. 3 **Case A** is with coupling angular momentum equal to zero. This case is referred to as "non-bias". After the contact, $\boldsymbol{L}_t$ distributes over the entire system. How fast it will be transferred to the base depends on factors like: pre-impact configuration, force impulse that occurs during the impact phase, post-impact control. In order to keep the base attitude stationary, the attitude stabilization devices[3] should work to compensate its deviation. As a result of the maximum torque restriction, the reaction wheels will most likely fail to accommodate the angular momentum transferred to the base in a short time. Hence, base rotational motion will occur.

One way for obtaining a distribution as the one depicted in **Case A** is using *reactionless manipulation* during the approach to the target. Planning of such reactionless trajectory however, is not a trivial problem.

If at the start of the capturing operation angular momentum is already stored in the reaction wheels and it is with equal magnitude and opposite direction to the one in the target, see **Case B**, the momentum of the entire system will be equal to zero, however, the transfer rate of $\boldsymbol{L}_t$ towards the attitude devices during the post-impact phase will be the same as in **Case A**. Hence, both distributions will yield identical results from the viewpoint of base attitude change.

B. Bias angular momentum in the manipulator

In both **Case B** and **Case C** the angular momentum of the entire system is equal to zero, however, the latter distribution leads to some advantages from the viewpoint of base attitude control after the contact with the target. **Case C** provides different alternatives for post-impact system control. One of them is again using the reaction wheels in order to compensate the base attitude change. An alternative approach uses the fact that after the contact, the angular momentum from the target could be canceled out with the one preloaded in the manipulator arm ($\boldsymbol{L}_{bm}$). Therefore, in the post-impact phase just the remaining amount of angular momentum in the base, manipulator and target should be redistributed in order the system to come to a complete stop. Since in this particular case the angular momentum that needs to be redistributed is actually zero, even locking the manipulator joints will lead to a successful completion of the capturing operation. We should note however, that if no post-impact control is applied, base attitude deviation might occur as a result of the impact force generated during the contact.

Since $\boldsymbol{L}$ is constant during the approach, cases **B** and **C** imply that momentum was already stored in the reaction

[2]This is clearly not the best possible control strategy for the post-impact phase, however, it permits easy comparison.

[3]Note that only reaction wheels are utilized for base attitude control.

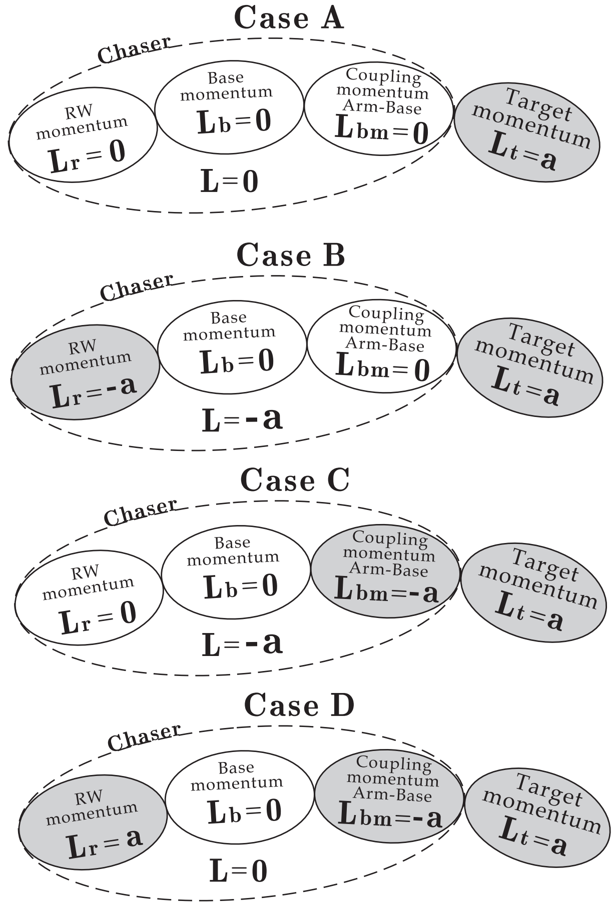

Fig. 3. Four cases of pre-impact angular momentum distribution.

wheels before the start of the approaching phase. **C** is considered as a case where the initial momenta on the reaction wheels are preliminarily transferred to the manipulator arm. Even with zero initial momenta on the chaser, , favorable momentum distribution can be obtained, as depicted in **Case D**. In general, the definition of a favorable angular momentum distribution can be summarized as follows:

$$\left.\begin{array}{l} |L^k_{bm}| \leq |L^k_t| \\ L^k_t\, L^k_{bm} < 0 \end{array}\right\} \tag{3}$$

where $k = \{x, y, z\}$ stand for the x, y and z components of a three dimensional vector. Equation (3) actually states that the momentum that should be preloaded in the manipulator has to be with smaller or equal magnitude and opposite direction to the one in the target. The limiting case when $\boldsymbol{L}_{bm} = -\boldsymbol{L}_t$, is referred to as "*full*" bias distribution and obtaining it is not always possible. Nevertheless, this case is included in the analysis as well, since it can give important insight into the problem. A bias momentum distribution which is not "*full*" and satisfies (3) is called "*partial*" (for more details see [34]).

C. Angular momentum management

Here, the problem of obtaining a desired angular momentum distribution in the chaser system during the approaching phase is discussed. Under the current assumptions, $\boldsymbol{L}$ remains constant during the approach to the target. However, it will not necessarily be equal to zero. In the general case, the system of reaction wheels is used for compensation of environmental torques, therefore before the start of the approach to the target $\tilde{\boldsymbol{H}}_{br}\dot{\boldsymbol{\phi}}_r$ can have a value different from zero. Solving (2) for the joint velocity rates, using $\boldsymbol{\omega}_b = 0$ (desired condition) and $\boldsymbol{P} = 0$, one obtains:

$$\dot{\boldsymbol{\phi}}_m = \tilde{\boldsymbol{H}}_{bm}^{+}(\boldsymbol{L} - \tilde{\boldsymbol{H}}_{br}\dot{\boldsymbol{\phi}}_r) + (\boldsymbol{E} - \tilde{\boldsymbol{H}}_{bm}^{+}\tilde{\boldsymbol{H}}_{bm})\dot{\boldsymbol{\xi}} \tag{4}$$

where $(\boldsymbol{E} - \tilde{\boldsymbol{H}}_{bm}^{+}\tilde{\boldsymbol{H}}_{bm})$ is the projector onto the null space of $\tilde{\boldsymbol{H}}_{bm}$, $\boldsymbol{E}$ is a unit matrix with proper dimensions, and $\dot{\boldsymbol{\xi}} \in R^n$ is an arbitrary vector. One important property of the null space component that was already mentioned is that joint velocities derived from it do not influence the momentum distribution whatsoever. Since $\boldsymbol{L}$ is constant during the approach, the only member of (4) that can redistribute the momentum in the chaser satellite is $\tilde{\boldsymbol{H}}_{br}\dot{\boldsymbol{\phi}}_r$. From the constraint $\boldsymbol{L}_b = 0$ it follows that, joint velocities obtained from (4) will result in such manipulator motion, that the rate of change of $\boldsymbol{L}_{bm}$ will be equal to the rate of change of $-\tilde{\boldsymbol{H}}_{br}\dot{\boldsymbol{\phi}}_r$. Such manipulator motion can be used in order to design a feasible approach to the target satellite (for more information see [34]).

IV. Impact Phase

In general, the second component of (4) can be utilized in order to additionally constrain the manipulator motion. During the impact phase, the simultaneous satisfaction of two requirements is desired: (i) base attitude minimization; (ii) successfully obtaining a firm grasp on the grasping facility, without pushing away the target satellite. The former requirement depends on the angular momentum transferred from the target to the spacecraft's base, and a way for its satisfaction will be discussed in the next section. The latter one is mainly related to the impedance characteristics of the end-effector and grasping fixture. Desired end-effector impedance characteristics can be assigned using the following equation:

$$\boldsymbol{M}_i\ddot{\boldsymbol{x}}_h + \boldsymbol{D}_i\Delta\dot{\boldsymbol{x}}_h + \boldsymbol{K}_i\Delta\boldsymbol{x}_h = \mathcal{F}_h \tag{5}$$

where $\boldsymbol{x}_h \in R^6$ is the end-effector position in the inertial frame. The impedance characteristics are: mass $\boldsymbol{M}_i \in R^{6\times6}$, viscosity $\boldsymbol{D}_i \in R^{6\times6}$, and stiffness $\boldsymbol{K}_i \in R^{6\times6}$. $\Delta\boldsymbol{x}_h$ is displacement of the end-effector position from a reference point in the inertial coordinate, and $\mathcal{F}_h$ are the external wrenches applied to the end-effector.

Rearranging (5) and integrating it once leads to:

$$\dot{\boldsymbol{x}}_h = {\boldsymbol{M}_i}^{-1}\int(\mathcal{F}_h - \boldsymbol{D}_i\Delta\dot{\boldsymbol{x}}_h - \boldsymbol{K}_i\Delta\boldsymbol{x}_h)dt \tag{6}$$

The above equation can be substituted in the equations of motion or alternatively, in the kinematic equation relating the joint and end-effector velocities, in order to obtain torque or velocity based impedance control, respectively.

In many cases obtaining desired end-effector impedance characteristics is necessary only in certain directions. Hence, from practical point of view, it can be applied in combination with the *distributed momentum control* (to be outlined in the next section), resulting in satisfaction of both requirements discussed at the beginning of this section.

V. Post-Impact Phase

After establishing contact with the target, $\boldsymbol{L}_t$ distributes over the chaser satellite. The objective is to manage the momentum in the entire system and slow down the arm motion in such a way that it does not affect the base attitude motion. A control law that satisfies this desired condition is proposed hereafter. It achieves minimal base attitude change, exploiting the dynamic coupling between the manipulator and spacecraft. It should be noted that, information about the forces acting between the end-effector and grasping point is not needed. This is advantageous since their precise measurements are difficult in general.

The angular momentum conservation equation has linear form at velocity level. It is much simpler than the equation of motion at acceleration level, and still fully expresses the system dynamics. This permits the formulation of a control law with simpler structure compared to post-impact control strategies already proposed [7]. We propose the following control:

$$\dot{\boldsymbol{\phi}}_m^d = \tilde{\boldsymbol{H}}_{bm}^{+}(\tilde{\boldsymbol{H}}_{bm}\dot{\boldsymbol{\phi}}_m^c + \tilde{\boldsymbol{H}}_b\boldsymbol{\omega}_b^c) \tag{7}$$

where $\dot{\boldsymbol{\phi}}_m^d$ is the desired value for the manipulator joint velocities whereas $\dot{\boldsymbol{\phi}}_m^c$ and $\boldsymbol{\omega}_b^c$ are current values measure by on-board sensors. Equation (7) is called *distributed momentum control* (DMC). If applied for controlling the arm during the post-impact phase of a tumbling satellite capturing operation, (7) will guarantee minimal base attitude deviation since it satisfies the momentum conservation law. As can be seen DMC is a velocity level feedback control including no information about the inertia characteristics of the target object, and its implementation is straightforward. The performance of the DMC has been discussed in [33] and [34]..

The DMC can go with a simple control law for the reaction wheels:

$$\boldsymbol{\tau}_r = \boldsymbol{K}_r\tilde{\boldsymbol{H}}_{bm}\dot{\boldsymbol{\phi}}_m^c \tag{8}$$

which can accelerate the reaction wheels according to the angular momentum in the arm, so that the arm motion will damp out, then the magnitude of $\dot{\boldsymbol{\phi}}_m^c$ in (7) and (8) will go smaller. Note that $\boldsymbol{K}_r$ is an appropriate gain matrix. This damping action continues until the reaction wheels will fully accommodate the angular momentum of the target $\boldsymbol{L}_t$.

VI. Conclusions

This paper discussed the problems related to the capture of a tumbling satellite by a space robot. From the viewpoint of angular momentum distribution, *bias momentum approach* for the approaching phase was proposed. Also the *distributed momentum control* for the post-impact phase was proposed.

As a summary of this paper, a simple example shall be given. Supposed that, in the initial state, the chaser robot has zero total angular momenta $\boldsymbol{L} = \boldsymbol{L}_b + \boldsymbol{L}_{bm} + \boldsymbol{L}_r = 0$, but the target has non-zero angular momentum $\boldsymbol{L}_t$. If the *bias momentum approach* is utilized, the manipulator arm should be controlled in the approaching phase to achieve the momentum distribution such that $\boldsymbol{L}_{bm} = -\boldsymbol{L}_t$ and $\boldsymbol{L}_r = \boldsymbol{L}_t$ while maintaining $\boldsymbol{L}_b = 0$; the base attitude should not be disturbed. Note that at the end of the approaching phase, the preloaded momentum value may not be $\boldsymbol{L}_t$ exactly, but $\hat{\boldsymbol{L}}_t$ with some difference from $\boldsymbol{L}_t$.

The impedance control at the contact phase facilitates smooth momentum exchange between the chaser and the target, so that $\boldsymbol{L}_{bm} \rightarrow \boldsymbol{L}_t - \hat{\boldsymbol{L}}_t$. Then the *distributed momentum control* is effective to maintain $\boldsymbol{L}_b = 0$ in the process $\boldsymbol{L}_{bm} \rightarrow 0$ in the post impact phase, and the motion of the chaser and target will completely stop when the conditions $\boldsymbol{L}_{bm} = 0$ and $\boldsymbol{L}_r = \boldsymbol{L}_t$ are achieved.

If without taking the *bias momentum approach*, the initial and the final conditions are exactly the same though, the post-impact control has to deal with a full amount of $\boldsymbol{L}_t$. But with the proposed approach, the post-impact effort shall be reduced into $\boldsymbol{L}_t - \hat{\boldsymbol{L}}_t$.

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