Stabilization and parameter identification of tumbling space debris with bounded torque in postcapture

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Abstract

This paper presents a new control scheme for the problem of a space robot after capturing an unknown tumbling target, such as space debris. Robotic capturing the target may destabilize the base of spacecraft and control torque is bounded which would affect the performance of attitude control system. To stabilize the base with bounded torque in postcapture scenario, a new control scheme which utilizes the control torque to balance angular momentum and motion of the manipulator to compensate limitation of the torque, is proposed. Considering uncertainties of the target, parameter identification technique for tumbling target with linear momentum is utilized to correct parameters of the controller. To verify validity and feasibility of the proposed concept, a planar space robot capturing small, medium and large target with or without linear momentum is studied. The results show that the whole system is stabilized finally and all the inertial parameters of the target converge to their real values.

Keywords: Tumbling targets, Linear momentum, Parameter identification, Bounded torque

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1. Introduction

Nowadays, more and more satellites have been launched into space. Without effieient ways to remove them after missions, the non-functioning satellites would threaten other satellites. The Iridium/Cosmos collision has made low earth orbit the most probable orbit site with collision potential [1]. A 2009 NASA study has shown that in order to keep the current LEO population at a constant level, at least five debris objects, in the 1 – 8 ton range, must be actively removed a year [2, 3]. The non-functioning satellites as well as space debris can be captured and removed by On-Orbit Servicing (OOS) satellites, and some OOS missions by space manipulators have been accomplished, such as ETS-VII, which performed the first autonomous rendezvous and capture with a robotic arm [1] or Orbit Express, which has proven autonomous rendezvous and capture operations [3]. Researchers typically separate the capture mission by a space manipulator into four main phases: the precapture, contact, postcapture, and compound stabilization[4]. However, robotic capturing of a noncooperative object such as a tumbling satellite in orbit may cause destabilization of the servicing spacecraft [5]. And the reaction of the manipulator motion disturbs the position and orientation of the robot base, then the coupling and coordination between the arm and the base becomes an important issue for successful operation [6].

A recursive method was first introduced by Wittenburg for multibody system dynamics modelling [7]. Compared with the standard analytical method like Lagrangian method, recursive method offers the possibility to do the calculation system for systems with many degrees-of-freedom (DOF), while analytical methods reach their limits [8]. The recursive dynamics for multibody system is still under development now, Gattringer [8] designed the controller for flexible joints based on recursive approaches. Hu [9] introduced a dynamics modelling method for multibody systems with variable-speed control moment gyroscopes in a recursive way.

For the control law, the attitude control system is supposed to be able to provide torques of any magnitude. This assumption is invalid in practice. If

this constraint is not taken into consideration, the base may not be stabilized [10]. For space robot, inspired by the famous falling-cat problem, the coupling between motion of manipulator and base can be utilized to stabilize the base. The null reaction space control (NRSC) was first conducted by Nenchev [11],
 35 which is used to design the motion of manipulator that induce the minimum vibration for the flexible structure mounted manipulator systems. It was also verified with the ETS-VII experimental facility [12]. Inna [13] designed the recursive adaptive controller for the tumbling target which is based on the NRSC in identification, and then got the law for motion of the manipulator which
 40 composed the minimal disturbance to the base's attitude.

Space manipulators have been developed so far, that do not equip dedicated sensors to measure joint acceleration and torque. Even if there are such sensors, the measurement will be under low signal/noise levels because space arms are usually operated very slowly and small acceleration is required for safety reason
 45 [6]. The identification technique based on the conservation of linear and angular momentum which does not require acceleration of the system was first conducted by Y.Murotsu [14] and it only requires angular and velocity of the joints and position, velocity, attitude and angular velocity of the base. Considering the gravity gradient torque, the technique is verified by data from ETS-VII [15].
 50 In [13], the identification technique for the tumbling target without the linear momentum was conducted.

In [13], the controller is based on the theory of momentum conservation, so the attitude control system cannot be used. Moreover, due to existence of angular momentum, the whole system cannot be stabilized finally and the ma-
 55 nipulator should move all the time to stabilize the base's attitude. In the future work of [13], the author pointed out that, momentum exchange mechanism control will be used to stabilize the whole system. In this paper, a novel control scheme for stabilizing the system considering torque boundary in postcapture is conducted. The torque is used to balance angular momentum of the system to
 60 achieve stabilization of the whole system finally and motion of the manipulator is utilized to compensate for the limitation of torque. In addition, parameter i-

dentification technique for tumbling target with linear momentum is given. The technique is based on the theory of momentum and the recursive least squares (RLS) method is used to obtain the inertial parameters of the unknown target.

65 The contents of this paper are organized as follows. In Sec. 2, the recursive dynamics and the inverse dynamics for space robot have been shown, and then the control scheme is introduced. The parameter identification technique for tumbling target with linear momentum is presented in Sec. 3. To validate the control scheme and the identification technique, simulation results are shown in
70 Sec. 4. Finally, the conclusions and future work are stated in Sec. 5.

2. Control Scheme

2.1. Regular labelling

Assuming that the number of bodies and joints are regularly labelled, or precisely, body i is connected to its inboard body j by joint i and $j < i$,
75 as shown in Figure.1. The attitude of body i with respect to body j can be described using the direction cosine matrix and O is the origin of inertial frame. It is assumed that $\boldsymbol{\omega}_i$ and $\boldsymbol{\omega}_j$ are the absolute angular velocity of body i and body j , respectively, $\mathbf{r}_i$ and $\mathbf{r}_j$ are the position vectors of the mass center of the bodies i and j in the reference frame, respectively, and C_i and C_j are the mass
80 centers of the two bodies. Q and P are the joint definition points on body j and i . $\mathbf{h}_i$ describes the relative motion of the joint i . In this paper, the inboard body number of body i is expressed by using the array of inscribed body $L(i)$.

2.2. Dynamic and inverse dynamic equation

The recursive dynamic equation for multibody system could be written as in [7]:

$$\mathbf{Z}\ddot{\mathbf{q}} = \mathbf{z} + \mathbf{u} \quad (1)$$

where $\mathbf{Z}$ is the generalized mass matrix, $\mathbf{z}$ is the generalized force array, $\ddot{\mathbf{q}}$ is
85 second-derivation with respect to time of generalized coordinates, and $\mathbf{u}$ is the control force of joints.

The Eq.(1) could be expanded as:

$$\begin{bmatrix} \underline{Z}_{1,1} & \cdots & \underline{Z}_{1,i} & \cdots & \underline{Z}_{1,n} \\ \vdots & & \vdots & & \vdots \\ \underline{Z}_{i,1} & \cdots & \underline{Z}_{i,i} & \cdots & \underline{Z}_{i,n} \\ \vdots & & \vdots & & \vdots \\ \underline{Z}_{n,1} & \cdots & \underline{Z}_{n,i} & \cdots & \underline{Z}_{n,n} \end{bmatrix} \begin{bmatrix} \ddot{\underline{q}}_1 \\ \vdots \\ \ddot{\underline{q}}_i \\ \vdots \\ \ddot{\underline{q}}_n \end{bmatrix} = \begin{bmatrix} \underline{z}_1 \\ \vdots \\ \underline{z}_i \\ \vdots \\ \underline{z}_n \end{bmatrix} + \begin{bmatrix} \underline{u}_1 \\ \vdots \\ \underline{u}_i \\ \vdots \\ \underline{u}_n \end{bmatrix} \quad (2)$$

where i refers to the number of the body. The inverse dynamic equation can be utilized to obtain the control force if second-order derivations of generalized coordinates are known.

The inverse dynamic equation can be written as:

$$\begin{bmatrix} -\underline{1} & \cdots & -\underline{0} \\ \vdots & \vdots & \vdots \\ -\underline{0} & \cdots & -\underline{1} \end{bmatrix} \begin{bmatrix} \underline{u}_1 \\ \vdots \\ \underline{u}_n \end{bmatrix} = \begin{bmatrix} \underline{z}_1 \\ \vdots \\ \underline{z}_n \end{bmatrix} - \begin{bmatrix} \underline{Z}_{1,1} \\ \vdots \\ \underline{Z}_{n,1} \end{bmatrix} \ddot{\underline{q}}_1 - \cdots - \begin{bmatrix} \underline{Z}_{1,n} \\ \vdots \\ \underline{Z}_{n,n} \end{bmatrix} \ddot{\underline{q}}_n \quad (3)$$

90 2.3. Control Scheme

The inverse dynamics is used to get the control scheme. For the free-floating space robot, the joint 1 between base and the inertial frame is virtual joint with six degrees of freedom, three for rotation and the others for transition in 3D. Since control force of joint 1 is external force and torque on base which can be included in the generalized force array $\underline{z}$, and suppose motion of other joints can be controlled ideally, then control force array $\underline{u}$ can be neglected. If $\ddot{\underline{q}}_1$ is known, the inverse dynamic of system can be written as:

$$\begin{bmatrix} \underline{z}_1 \\ \vdots \\ \underline{z}_n \end{bmatrix} - \begin{bmatrix} \underline{Z}_{1,1} \\ \vdots \\ \underline{Z}_{n,1} \end{bmatrix} \ddot{\underline{q}}_1 = \begin{bmatrix} \underline{Z}_{1,2} \\ \vdots \\ \underline{Z}_{n,2} \end{bmatrix} \ddot{\underline{q}}_2 + \cdots + \begin{bmatrix} \underline{Z}_{1,n} \\ \vdots \\ \underline{Z}_{n,n} \end{bmatrix} \ddot{\underline{q}}_n \quad (4)$$

The Eq.(4) could be written in a compact form as:

$$\underline{H}\ddot{\underline{q}}' = \underline{b} \quad (5)$$

where

$$\underline{H} = \begin{bmatrix} \underline{Z}_{1,2} & \cdots & \underline{Z}_{1,n} \\ \vdots & \vdots & \vdots \\ \underline{Z}_{n,2} & \cdots & \underline{Z}_{n,n} \end{bmatrix} \quad (6)$$

$$\underline{q}' = \begin{bmatrix} \ddot{q}_2 & \cdots & \ddot{q}_n \end{bmatrix}^T \quad (7)$$

$$b = \begin{bmatrix} \underline{z}_1 \\ \vdots \\ \underline{z}_n \end{bmatrix} - \begin{bmatrix} \underline{Z}_{1,1} \\ \vdots \\ \underline{Z}_{n,1} \end{bmatrix} \ddot{q}_1 \quad (8)$$

And the solution for q' is obtained by integrating the following formulation::

$$\underline{\ddot{q}}' = \underline{H}^+ b - (\underline{E}_{n-1} - \underline{H}^+ \underline{H}) y \quad (9)$$

where $\underline{H}^+$ denotes the pseudo inverse of matrix $\underline{H}$, and y is an arbitrary vector with units of angular accelerations.

2.4. Control law for stabilizing the base

For stabilizing the base, the control law for attitude angular acceleration is:

$$\ddot{\underline{q}}_1 + K_D \dot{\underline{q}}_1 + K_P \underline{q}_1 = 0 \quad (10)$$

where $\underline{q}_1$ and $\dot{\underline{q}}_1$ is attitude angular and angular velocity of the base separately.

95 If matrix K_D and K_P are both positive define, $\underline{q}_1$ will approach to zero [16].

To stabilize the base, control torque and motion of manipulator are planned together. The torque is used to balance angular momentum of the system with respect to mass center, while motion of the manipulator is used to compensate the limitation of torque. Considering boundary of the torque, the equation

100 between the torque M and angular momentum L with respect to the mass center can be described like in Figure 2.

Suppose the max angular momentum is L_{max} , and the max torque is M_{max} , the proportion factor is K with the units of s^{-1} , so control torque is showed in

Eq.(11).

$$M = \begin{cases} -M_{max} & \text{if } L \geq L_{max} \\ K \cdot L & \text{if } L < L_{max} \text{ and } L \geq -L_{max} \\ M_{max} & \text{if } L \leq -L_{max} \end{cases} \quad (11)$$

105 3. Parameter Identification

For space robot, orbital dynamics are often neglected, which means that robot is free-floating and observes momentum conservation with respect to mass center without external forces or torques except gravity. However, due to the measurement error, velocity of the target does not equal to that of the robot,
 110 then the combined system, robot with target, seems to have initial linear and angular momentum after capturing the tumbling target. It is assumed that, shortly after the manipulator grasps the target, target will be rigidized relative to the end effector. The momentum-based identification to estimate the inertial parameters of target after capture, without the knowledge of its initial angular
 115 momentum or linear momentum, is now derived. The target is labelled as n while base is labelled as 1 for simplify, the unknown parameters to be identified are m_n , $\mathbf{c}_n$ and $\mathbf{I}_n$, which denote mass, position of center of mass, and inertial tensor of the target in the body frame of the target. And $\mathbf{c}'_n$ and $\mathbf{I}'_n$, are in inertial frame and $\mathbf{c}_n$ and $\mathbf{I}_n$ are in body frame of the target.

120 3.1. Identification of mass and mass center

The kinematic and dynamic parameters of system, except for the unknown target, are assumed to be known a priori, and it is also assumed that joint angles and rates are available while the joint between end-effector and target is locked to stabilize the target. The linear momentum $\mathbf{P}$ and angular momentum $\mathbf{L}$ are now written by separating terms with the known and measured quantities from those involving unknown parameters of the target.

$$\mathbf{P} = \sum_{i=1}^{n-1} m_i \dot{\mathbf{r}}_i + m_n \dot{\mathbf{r}}_n \quad (12)$$

$$\mathbf{L} = \sum_{i=1}^{n-1} (\mathbf{I}_i \dot{\boldsymbol{\omega}}_i + m_i \mathbf{r}_i \times \dot{\mathbf{r}}_i) + \mathbf{I}_n \dot{\boldsymbol{\omega}}_n + m_n \mathbf{r}_n \times \dot{\mathbf{r}}_n \quad (13)$$

According to momentum theorem, the changes of linear and angular momentum of the system equal to the integration of external force and torque.

$$\mathbf{P}(t_f) - \mathbf{P}(t_0) = \int_{t_0}^{t_f} \mathbf{F}(t) dt \quad (14)$$

$$\mathbf{L}(t_f) - \mathbf{L}(t_0) = \int_{t_0}^{t_f} \mathbf{M}(t) dt \quad (15)$$

Suppose the initial linear and angular momentum is $\mathbf{P}(0)$ and $\mathbf{L}(0)$, and external force and torque are known all the time. Combining Eq.(12), (13), (14) and (15), the identification equation for m_n and $\mathbf{c}'_n$, can be written as:

$$\begin{aligned} & \left[\begin{array}{cc} \mathbf{U}(t) - \mathbf{U}(0) - \int_0^t \mathbf{F}(t) dt & \tilde{\boldsymbol{\omega}}_{n,t} \underline{A}_{n,t} - \tilde{\boldsymbol{\omega}}_{n,0} \underline{A}_{n,0} \end{array} \right] \left[\begin{array}{c} \frac{1}{m} \\ \mathbf{c}'_n \end{array} \right] \\ & = -[\mathbf{W}(t) - \mathbf{W}(0)] \end{aligned} \quad (16)$$

where

$$\mathbf{U}(t) = \sum_{i=1}^{n-1} m_i \mathbf{v}_{i,t} \quad (17)$$

$$\mathbf{W}(\mathbf{t}) = \mathbf{v}_{\mathbf{n}-1,\mathbf{t}} + \tilde{\boldsymbol{\omega}}_{\mathbf{n}-1,\mathbf{t}} \mathbf{b}_{\mathbf{n}-1,\mathbf{t}} \quad (18)$$

$\tilde{\mathbf{v}}$ indicates the following cross matrix for a vector $\mathbf{v} = [v_1, v_2, v_3]^T$.

$$\tilde{\mathbf{v}} = \begin{bmatrix} 0 & -v_3 & v_2 \\ v_3 & 0 & -v_1 \\ -v_2 & v_1 & 0 \end{bmatrix} \quad (19)$$

And the subscript t refers to time. However, $\mathbf{c}'_n$ would change due to rotation of the target which is constant in body frame of the target. Next, it is essential to project $\mathbf{c}'_n$ in inertial frame via the rotation matrix.

$$\mathbf{c}_n = \underline{A}_n \mathbf{c}'_n \quad (20)$$

Combining Eq.(16) and (20), the identification equation for m_n and $\mathbf{c}_n$ can
 125 be written as:

$$\begin{bmatrix} \mathbf{U}(t) - \mathbf{U}(0) - \int_0^t \mathbf{F}(t) dt & \tilde{\omega}_{n,t} \underline{A}_{n,t} - \tilde{\omega}_{n,0} \underline{A}_{n,0} \end{bmatrix} \begin{bmatrix} \frac{1}{m} \\ \mathbf{c}_n \end{bmatrix} = -[\mathbf{W}(t) - \mathbf{W}(0)] \quad (21)$$

3.2. Identification of inertial tensor

After m_n and $\mathbf{c}_n$ become known, linear momentum of the system can be known, and then inertia tensor of the target would be obtained. Like $\mathbf{c}'_n$, inertial tensor $\mathbf{I}'_n$ would change due to rotation of the target, which follows:

$$\mathbf{I}_n = \underline{A}_n \mathbf{I}'_n \underline{A}_n^T \quad (22)$$

By combining Eq.(12), (13), (14), (15), (21) and (22) and $\mathbf{c}_n$, the identification equation for $\mathbf{I}_n$ would be written as:

$$\begin{aligned} & [\mathbf{K}(\mathbf{t}) - \mathbf{K}(\mathbf{0})][\mathbf{I}'\#] = \\ & \int_0^t \mathbf{M}(\mathbf{t}) dt - [\mathbf{G}(\mathbf{t}) - \mathbf{G}(\mathbf{0})] + [\mathbf{J}(\mathbf{t}) - \mathbf{J}(\mathbf{0})] + [\mathbf{S}(\mathbf{t}) - \mathbf{S}(\mathbf{0})] \mathbf{c}_n \end{aligned} \quad (23)$$

where

$$\mathbf{G}(t) = \sum_{i=1}^{n-1} \mathbf{I}_i \boldsymbol{\omega}_{i,t} + m_i \mathbf{r}_{i,t} \times \dot{\mathbf{r}}_{i,t} \quad (24)$$

$$\mathbf{J}(t) = \left[\widetilde{\mathbf{P}(t)} - \sum_{i=1}^{n-1} m_i \tilde{\mathbf{r}}_{i,t} \right] (\mathbf{r}_{n-1,t} + \mathbf{b}_{n-1,t}) \quad (25)$$

$$\mathbf{K}(t) = \underline{A}_{n,t} [\# (\underline{A}_{n,t}^T \boldsymbol{\omega}_{n,t})] \quad (26)$$

$$\mathbf{S}(t) = \left[\widetilde{\mathbf{P}(t)} - \sum_{i=1}^{n-1} m_i \tilde{\mathbf{r}}_{i,t} \right] \underline{A}_{n,t} \quad (27)$$

And $[\#\bullet]$ indicates the following operation matrix for a vector $\mathbf{v} = [v_1, v_2, v_3]^T$.

$$[\#\mathbf{v}] = \begin{bmatrix} v_1 & v_2 & v_3 & 0 & 0 & 0 \\ 0 & v_1 & 0 & v_2 & v_3 & 0 \\ 0 & 0 & v_1 & 0 & v_2 & v_3 \end{bmatrix} \quad (28)$$

The vector $[\bullet\#]$ indicates the following operation vector

$$[\mathbf{I}\#] = \begin{bmatrix} I_{11} & I_{12} & I_{13} & I_{22} & I_{23} & I_{33} \end{bmatrix} \quad (29)$$

for a symmetric matrix

$$\mathbf{I} = \begin{bmatrix} I_{11} & I_{12} & I_{13} \\ I_{12} & I_{22} & I_{23} \\ I_{13} & I_{23} & I_{33} \end{bmatrix} \quad (30)$$

4. Simulation

130 In this section, numerical simulations of different scenarios are carried out to validate the control scheme. In all scenarios, the end-effector of space robot grasps the target firmly, the process of grasping is ignored, and all the joints are locked at the beginning.

135 The planar model is studied as illustrated in Figure 3, which has a 3DOF manipulator, the parameters of the whole system are the same as those in [13], and the sampling period for parameter identification is 0.1s. Parameters of the model are shown in Table 1.

Table 1: Simulation model parameters

Body	Mass(kg)	I(kgm ²)	Dimension(m)
Base	500	83.61	1×1
Link1	10	1.05	1
Link2	10	1.05	1
Link3	10	1.05	1
Target1	125	5.2	0.5×0.5
Target2	250	10.41	0.5×0.5
Target3	500	20.83	0.5×0.5

In planar model test, initial angular velocity of the system is 0.2rad/s, while for linear momentum, initial velocity of the system is $V_x = 20m/s$ and $V_y =$

140 $20m/s$ or $V_x = V_y = 0$. The simulation shows the results of small, medium and large target compared to the system with or without initial velocity.

In Eq.(10), matrix K_D and K_P are chosen as: $K_D = diag(10, 10, 10)$ and $K_P = diag(10, 10, 10)$.

For the controller in Eq.(11), $M_{max} = 40Nm$, $L_{max} = 40kgm^2/s$, so $K =$
145 $-1s^{-1}$.

At first, in Eq.(9), vector $\mathbf{y} = [0, 0, 0]^T$, then if control torque is sufficiently small which means that angular momentum with respect to mass center is zero, the vector y is selected to stabilize the manipulator, joint 3 stops first and then joint 2 and 1 stop together. The special motion of the manipulator
150 can be achieved because simulation model has the redundancy to meet the requirements of base's attitude and special motion of joint 3. Moreover, when angular momentum with respect to mass center is zero, the whole system can be stabilized finally.

Before simulation, it is supposed that inertial parameters of the unknown
155 target are: $m_n = 10kg$, $I_{zz} = 1kgm^2$ and $c_x = c_y = 0.01m$. And the equations of identification technique are solved by RLS method, which is an online algorithm.

4.1. Model Test Case 1, $\mathbf{P}(0) = \mathbf{0}$

4.1.1. Medium Target, $m_n = 250kg$

This section shows the results to validate the control scheme in this paper
160 in order to stabilize the whole system. The results are compared with the those in [13].

Figure 4a shows the results from [13], initial angular momentum of the in simulation is different, but the gap does not affect the results and it can be clearly seen that the joints should move all the time to stabilize the base. However,
165 in Figure 4b, the whole system including the base and manipulator is stabilized finally, and the settling time for it is 17.7s.

For joints, joint 3 stops first, and then joint 2 and joint 1 stop together, and the motion of the joints does not affect the base's attitude, this phenomenon results from the redundancy of the manipulator.

170 4.1.2. *Small and Large Target, $m_n = 125kg$, and $m_n = 500kg$*

Then, the scenario for small and large target are studied. The base's attitude, control torque and motion of joints have the same tendency with those from medium target, so they are omitted here, and only estimation results are shown in Figure 7 and 8.

175 For parameter identification, m_n , I_n , c_x and c_y all converge to their real values in different simulations, and final estimation results are shown in Table 2.

It is indicated that m_n , c_x and c_y usually converge to their real values faster than I_n . The reason for this phenomenon is that for m_n , c_x and c_y , dimension
180 of the identification matrix is 3×4 , but for I_n , it is 1×1 . And the precision of c_x and c_y would influence I_n , which can be found in Eq.(23).

Table 2: Parameters estimation results, $\mathbf{P}(0)=\mathbf{0}$

	m_n	c_x	c_y	I_{zz}
Small	125.00051	0.249988	0	5.209904
Medium	250.00077	0.249993	0	10.42080
Large	500.00124	0.249996	0	20.83692

In these simulations, the whole system can be stabilized finally. However, the larger target, the longer time for stabilization. The settling time is $17.7s$, $21.71s$, $26.99s$ for small, medium and large target, respectively. The different settling
185 time may result from that the system with the larger target would require more time to balance the disturbed angular momentum, since the initial angular velocity is constant at the beginning, considering boundary of the torque.

The identification technique is utilisable for tumbling target without linear momentum, and results for systems with both linear and angular momentum
190 are shown next.

4.2. Model Test Case 2, $\mathbf{P}(0) \neq \mathbf{0}$

For simulation model with linear momentum, control scheme is the same as before. According to the simulation results, attitude of base, motion of the joints and control torque are the same with the models without linear momentum, this may result from the fact that the control scheme depends on angular momentum with respect to the mass center of the system, and linear momentum in simulation does not affect it if inertial parameters of the target are known. As for the parameter identification, the tendency of the inertial tensor has changed a lot comparing with before, and the estimation results of I_{zz} are shown in Figure 9.

The estimation results converge to their real values, and they are shown in Table 3.

Table 3: Parameter estimation results, $\mathbf{P}(0) \neq \mathbf{0}$

	m_n	c_x	c_y	I_{zz}
Small	125.00051	0.249988	0	5.258047
Medium	250.00077	0.249993	0	10.50263
Large	500.00125	0.249996	0	20.72700

The identification technique in this paper is useful for the system with initial angular and linear momentum. However, the tendency of identification I_{zz} is different with the results in Figure 6c, 7c and 8c. This may result from the fact that initial linear momentum has the influence on the identification of I_{zz} which can be found in Eq.(22). And in Eq.(16), the gap between computed initial linear momentum and the real one is more obvious than that in system without initial linear momentum. The difference results in the different tendency of I_{zz} .

From the results, settling time for the system is 17.7s, 21.71s and 26.92s for small, medium and large target separately which is close to those from the system without initial linear momentum, and the base's attitude, motion of the manipulator and control torque are the same as system without the linear momentum, which means that the different identification results of the unknown

215 target especially I_{zz} do not affect the system obviously. This may result from
that inertial tensor of the target is small compared with that of the system
if mass and mass center of the target are known, and it does not affect the
dynamics of system notably.

5. Conclusion

220 A new control scheme for space robot to stabilize the whole system in the
postcapture of capturing an unknown tumbling target, such as orbital debris, is
presented in this paper. Considering the bounded torque for balancing angular
momentum of the system, motion of the manipulator is used to help to stabilize
the base. Due to uncertainties of the unknown target and measurement errors
225 before capture, parameter identification technique for tumbling target with lin-
ear momentum is used to correct the controller. Two scenarios of capturing an
unknown tumbling target with or without initial linear momentum are simulat-
ed to validate the control scheme. The results show that inertial parameters of
the target could be gotten by the identification technique and the whole system
230 including base and manipulator can be stabilized finally. In the future work, the
control law with avoidance of self-collisions and motion of manipulator based
on the optimal control theory will be developed.

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Figure 1: Diagram of two adjacent bodies

Figure 2: Control torque considering boundary

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Figure 3: Simulation model

Figure 4: Different results from [13] and this paper with $m_n = 250kg, \mathbf{P} = \mathbf{0}$

Figure 5: Attitude and the control torque with the control scheme, $m_n = 250kg, \mathbf{P} = \mathbf{0}$

Figure 6: Parameter estimation results, $m_n = 250kg, \mathbf{P} = \mathbf{0}$

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Figure 7: Parameter estimation results, $m_n = 125kg, \mathbf{P} = \mathbf{0}$

Figure 8: Parameter estimation results, $m_n = 500kg, \mathbf{P} = \mathbf{0}$

Figure 9: Parameter estimation results of $I_{zz}, \mathbf{P} \neq \mathbf{0}$

Figure 1: Diagram of two adjacent bodies

Figure 2: Control torque considering boundary

Figure 3: Simulation model

(a) Results of ARLC in [13]

(b) Results of the control scheme

Figure 4: Different results from [13] and this paper with $m_n = 250kg$, $\mathbf{P} = \mathbf{0}$

(a) Base attitude angle

(b) Control torque

Figure 5: Attitude and the control torque with the control scheme, $m_n = 250kg$, $\mathbf{P} = \mathbf{0}$

(a) Estimated mass

(b) Estimated mass center

(c) Estimated inertial tensor

Figure 6: Parameter estimation results, $m_n = 250kg$, $\mathbf{P} = \mathbf{0}$

(a) Estimated mass

(b) Estimated mass center

(c) Estimated inertial tensor

Figure 7: Parameter estimation results, $m_n = 125\text{kg}$, $\mathbf{P} = \mathbf{0}$

(a) Estimated mass

(b) Estimated mass center

(c) Estimated inertial tensor

Figure 8: Parameter estimation results, $m_n = 500\text{kg}$, $\mathbf{P} = \mathbf{0}$

(a) Small target

(b) Medium target

(c) Large target

Figure 9: Parameter estimation results of I_{zz} , $\mathbf{P} \neq \mathbf{0}$