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# Finite time attitude takeover control for combination via tethered space robot

Yingbo Lu[a,b], Panfeng Huang[a,b,*], Zhongjie Meng[a,b], Yongxin Hu[a,b], Fan Zhang[a,b], Yizhai Zhang[a,b]

[a] *Research Center for Intelligent Robotics, School of Astronautics, Northwestern Polytechnical University, Xi'an 710072, China*
[b] *National Key Laboratory of Aerospace Flight Dynamics, Northwestern Polytechnical University, Xi'an 710072, China*

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## ABSTRACT

Up to April 6, 2016, there are 17,385 large debris in orbit around the Earth, which poses a serious hazard to near-Earth space activities. As a promising on-orbit debris capture strategy, tethered space robots (TSRs) have wide applications in future on-orbit service owing to its flexibility and great workspace. However, lots of problems may arise in the Tethered Space Robots (TSRs) system from the approaching, capturing, postcapturing and towing phases. The postcapture combination attitude takeover control by the TSR is studied in this paper. Taking control constraints, tether oscillations and external disturbances into consideration, a fast terminal sliding mode control (FTSMC) methodology with dual closed loops for the flexible combination attitude takeover control is designed. The unknown upper bounds of the uncertainties, external disturbances are estimated through adaptive techniques. Stability of the dual closed loop control system and finite time convergence of system states are proved via Lyapunov stability theory. Besides, null space intersection control allocation was adopted to distribute the required control moment over TSR's redundant thrusters. Simulation studies have been conducted to demonstrate the effectiveness of the proposed controller with the conventional sliding mode control(SMC).

## 1. Introduction

On-orbit capture technologies have many potential applications, including on-orbit maintenance, on-orbit upgrading, on-orbit replenishing of consumables, on-orbit assembly and space debris cleaning. Based on this definition, space debris are uncontrolled space objects serving no function, such as failure or malfunction satellites, jettisoned components, and collision shrapnel [1]. The low Earth orbit has nearly reached saturation with rogue objects caused by millions of space debris, and high-density wreckages make a very serious hazard for mankind infrastructure. In order to change the severe status in GEO orbit, researchers have proposed many methods [2–17] for space debris, including tentacles capturing [2], single arm capturing [5–8], multiple arms capturing [9], net capturing [10,11], harpoon mechanism capturing [12] and tethered space robots capturing [13–17]. Tethered space robot(TSR) which is consist of a gripper, a nonelectro-dynamic space tether and a space platform (Fig. 1) whose objective is to transport a target into the graveyard or disposal orbit similar to space tug [18–22] and ROGER [23]. Tethered space robot (TSR) has wide applications in future on-orbit servicing missions owing to its flexibility, portability, larger operational radius and security. A wide range of problems may arise in various aspects, including visual servoing technology, coordinated orbit and attitude control, postcapture control, detumbling combination (chaser and target satellite) and towing.

The collision between the chaser and target leads to a tumbling of the combination, which makes the control of the combination extremely complicated. To our reassurance, postcapture attitude takeover control has received some attention and a little work has been done in the last decades. Panfeng Huang [8] designs a reconfigurable control system for attitude takeover control in post-capture of target spacecraft using space robot. Panfeng Huang [15] also presents a robust adaptive backstepping controller to achieve stabilization of a tumbling tethered space robot target combination. Satoko Abiko [24] addresses an impedance control for a free-floating space robot in the grasping of a tumbling target with model uncertainty. Wenfu Xu [25] adopts the approach of manipulator motion to overcome the base attitude lean and re-orientating simultaneously, Wenfu Xu [26] also developed a dynamic model for a space robot with flexible appendages to capture and repair the large flexible spacecraft. F. Aghili [27] focuses on the

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[*] Corresponding author at: Research Center for Intelligent Robotics, School of Astronautics, Northwestern Polytechnical University, Xi'an 710072, China.
*E-mail address:* pfhuang@nwpu.edu.cn (P. Huang).

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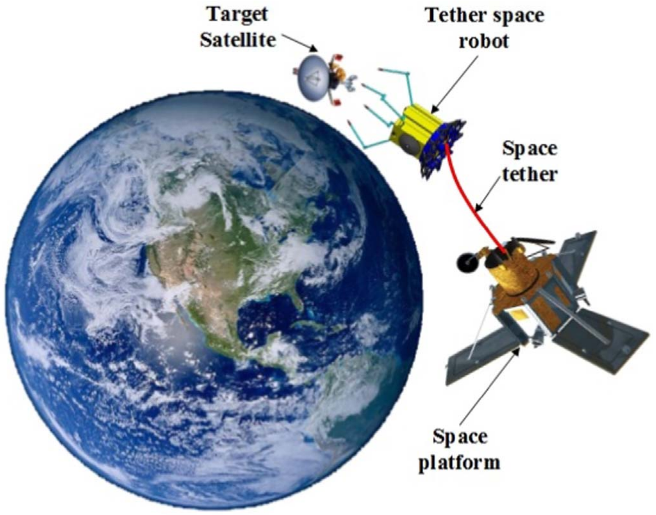

**Fig. 1.** TSR system.

guidance of a robot manipulator to capture a tumbling satellite with unknown dynamics parameters and then bring it to state of rest (detumbling).

Most of the attitude control schemes mentioned above can only achieve asymptotic stability, which means that the rotational motion of a combination can be converged to a desired status as time trends to infinity. During postcapture phase, the inertia matrix of the combination cannot be exactly known, and the combination is always subject to external disturbances. Due to its faster convergence rate, higher accuracies and better robustness against uncertainties, finite-time control has gained increasing attention in recent years, and many related works have been published in this research field. Ning Zhou [28]investigated the control problem of finite-time attitude synchronization and tracking for a group of rigid spacecraft in the presence of environmental disturbances. Shunan Wu [29] investigated two robust controllers based on the error quaternion and sliding mode control approach to achieve finite time stabilization. Zhankui Song [30] proposed a fast terminal sliding mode control with double closed loops for the rigid spacecraft attitude control.

Motivated by [28–30], we intends to propose a finite time continuous terminal sliding mode controller to realize attitude takeover stabilization of a tumbling tethered flexible combination considering tether oscillation and external disturbances in this paper. The remainder of the paper is organized as follows: In Section 2, the kinematics and dynamics of flexible combination are summarized. In Section 3, the details of the design procedure and the system stability analysis for the proposed FTSMC controller as well as modal velocity feedback compensator controller are given. In Section 4, control reallocation based on null-space intersections of combination spacecraft is introduced. Sections 5 and 6 presents numerical simulation results and conclusions respectively.

## 2. Problem formulation

### 2.1. Dynamic modeling of TSRS for post target capturing

The designed TSR is designed to be a hexahedron with a total mass of 10 kg and a length of 480 mm and a diameter of 260 mm, and is principally composed of seven subsystems, including structure subsystem, thermal control subsystem, power supply subsystem, propulsion subsystem, guide, navigation, control (GNC) subsystem, visual perception subsystem and central processing subsystem. On the upper panel are mounted 2 stereo cameras, 2 light emitting diodes (LEDs) and a 3-finger gripping element. The motion to the target and rotations will be performed by a cold gas propulsion system using 12 thrusters of 5 N thrust each, a tank containing of about 1 kg liquid nitrogen. IMU is used for pose measurement.

A schematic of the model, as well as the generalized coordinates used to describe the TSR capturing are illustrated in Fig. 2, the system is comprised of a space platform, space tether, TSR and target. In the postcapturing phase, TSR and target are rigidly connected, we deem the combination as a flexible spacecraft. To simplify the description, we firstly define some frames. Let $OXYZ$ be the geocentric inertia frame with its origin at the mass center of the earth, and we use it to determine the orbit position of the combination.

The origin of the platform orbital frame $Oxyz$, is located at the centroid of the space platform. The $x$-axis points from the center of the Earth to the centroid of the space platform, $y$-axis axis along the local horizontal, $z$-axis is found using the right hand orthogonal frame. $O_b x_b y_b z_b$ denotes the combination body frame with its origin $O_b$ located at the centroid of the combination. $l$ denotes the tether length from space platform to the tether attachment. $\alpha$ and $\beta$ are the in-plane angle and out of plane angle respectively. $A$ is the tether attachment point and $\boldsymbol{d}_1$ represents the corresponding position vector from point A to the centroid of space platform.

The dynamics of a flexible combination are given by [32]

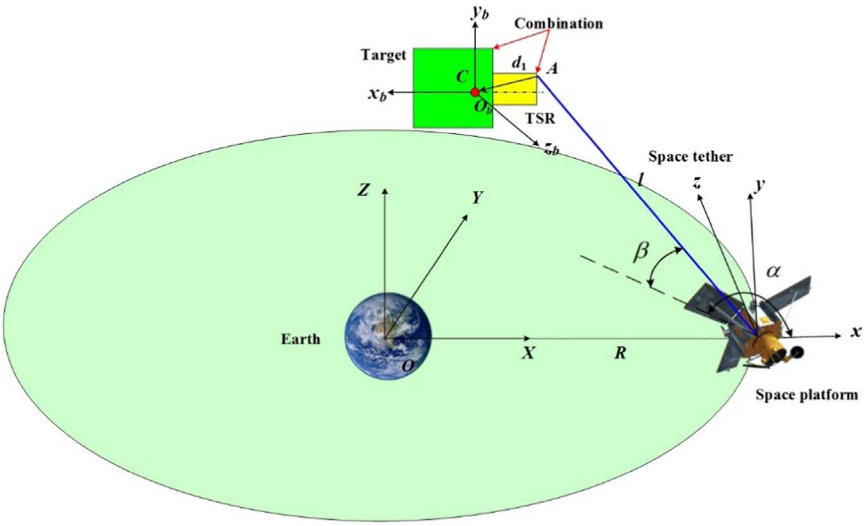

**Fig. 2.** Target capture of the tethered space robot.