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Coordinated coupling control of tethered space robot using releasing characteristics of space tether

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Abstract

Tethered space robot (TSR) is a new concept of space robot, which is released from the platform satellite, and retrieved via connected tether after space debris capture. In this paper, we propose a new coordinate control scheme for optimal trajectory and attitude tracking, and use releasing motor torque to instead the tension force, since it is difficult to track in practical. Firstly, the 6-DOF dynamics model of TSR is derived, in which the dynamics of tether releasing system is taken into account. Then, we propose and design the coordinated coupled controller, which is composed of a 6-DOF sliding mode controller and a PD controller tether's releasing. Thrust is treated as control input of the 6-DOF sliding mode controller to control the in-plane and out-of-plane angle of the tether and attitude angles of the TSR. The torque of releasing motor is used as input of PD controller, which controls the length rate of space tether. After the verification of the control scheme, finally, the simulation experiment is presented in order to validate the effectiveness of this control method. The results show that TSR can track the optimal approaching trajectory accurately. Simultaneously, the attitude angles can be changed to the desired attitude angles in control period, and the terminal accuracy is $\pm 0.3°$.

Keywords: Tethered space robot (TSR); Coordinated control; Sliding mode control; PD control; Space tether; Thruster

1. Introduction

Since the swift growth of space debris especially in low space orbit, the space debris removal is an urgent issue all around the world (Zhai et al., 2009; Boning and Dubowsky, 2010). Researchers have proposed different devices to clean the space junk, including the rigid manipulators (Wang and Xie, 2012; Xu et al., 2012), space web (Zhai et al., 2009), space tug (Aslanov and Yudintsev, 2013), and some other novel devices (Marin et al., 1995). Although these capture devices all have their own special characteristics, they also have many limitations. These years, as the space tether is getting more attention (Kokubun and Fujii, 1996; Tang et al., 2011), some applications of the space tether are studied a lot by researchers throughout the world. In this background, our team proposed Tethered space robot (TSR) in 2009, which is a new kind of on-orbit mechanism for uncontrolled satellite capture (Wang et al., 2014, 2015; Huang et al., 2015). The TSR system consists of platform satellite, space tether, and an operation robot, which are shown in Fig.1. The mission scenario is that operation robot is released from the robot platform via the space tether, then approaches the target automatically. After accomplish on-orbit tasks, namely debris capture through operation arm and operation hand, the compound will be retrieved via tether, and then de-orbit to grave orbit. The TSR has larger

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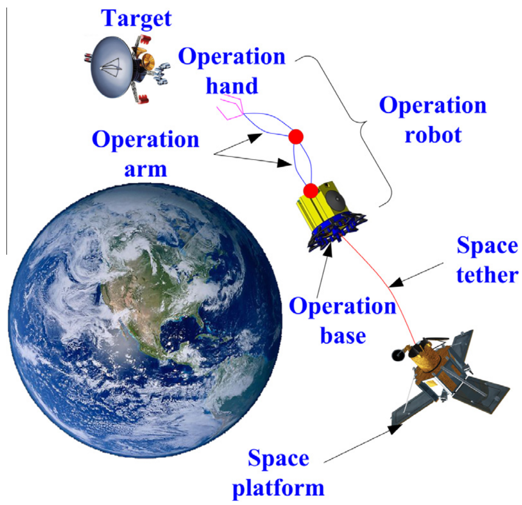

Fig. 1. The construction of TSR.

operational radius and greater flexibility compared with traditional space robot, because the combination of operation robot and space tether can be seen as an extended space arm.

In the approaching phase, the terminal robot flies towards the target automatically under the control scheme. At the end of this phase, the operation robot is required to arrive at the desired position and keep relative attitude stable, so that the robot will have a nice beginning in next phase. Therefore, the key technology of the problems in approaching phase is optimal trajectory planning, control tracking, and relative attitude stability. This paper carries out the research according to this key technology. This paper provides a coordinated coupling control strategy to track the optimal trajectory by using tether releasing mechanism, space tether and on-board thrusters.

It is necessary to select a proper method for establishing optimal trajectory planning model. Optimal trajectory planning problem is a kind of optimal control process under some constraint conditions, such as path, control, or other constraints. The optimal index is fuel consumption or approach time. For optimal trajectory planning problem, Ulybyshev presented a trajectory optimization method for low-thrust spacecraft proximity maneuvering at near-circular orbits, which used the discretization of a spacecraft trajectory on segments and sets of pseudoimpulses for each segment (Huang et al., 2014; Ulybyshev, 2011; Kampen et al., 2008). Suzuki presented a sequential goal programming approach, which was considered not only well-defined flight trajectory problems but also ill-defined problems, and a fuzzy decision making method was applied for the optimization that were not precisely prioritized in this method (Suzuki and Yoshizawa, 1994). An interval optimization was proposed according to the fixed-time multiple impulse rendezvous and docking problem (Kampen et al., 2010).

The above methods indicated the development of optimal control problems in recent years. However, they focused on long-distance optimal trajectory planning. In this paper, the releasing length of tether is about 200 m level. Therefore, universal trajectory planning method should be used for short distance situation. The pseudospectral method is a popular direct method that parameterizes the state and control variables using orthogonal polynomials such as Legendre and Chebyschev polynomial (Benson, 2004; Fahroo and Ross, 2006; Guo et al., 2012). The use of global polynomials, together with the Gauss quadrate collocation points, is known to provide accurate approximations that converge exponentially for problems whose solutions are smooth (Garg et al., 2010). This method is widely used for many trajectory optimization applications. Therefore, it is appropriate to select this method to obtain the optimal approaching trajectory of TSR.

For coordinated control using tether, Nakamura et al. discussed the collaborative control of tension (controlled by the service satellite) and thruster (controlled by tethered robot) in approaching the target of the tethered retriever but did not consider the attitude (Yuya et al., 2005). Nohmi designed a tethered space robot, connected to a mother spacecraft through a tether. The tethered subsystem's attitude can be controlled by the tether tension through its own link motion, and the tethered subsystem rotates when its mass center deviates from equilibrium, controlled by the arm (Masahiro, 2004). They also developed a space robot attached to a spacecraft through a tether. The spacecraft-mounted manipulator generated the necessary initial momentum for the space robot and adjusted its trajectory by controlling tether tension (Masahiro et al., 2001). Mori proposed the concept of tethered satellite cluster systems whose parts were connected by tethers. He established the coordinated control method using tension and thrust, which decreased the fuel consumption of the thruster and improved control precision (Osamu and Saburo, 2001). Huang proposed an optimal coordinate control scheme for the TSR based on the discretized mathematical model (Huang et al., 2015). A coordinated fault-tolerant nonlinear control design was presented by Godard (Godard and Tan, 2008) to control the attitude of a satellite using movement of the tether attachment points, and his method examined cases when tether deployment suddenly stops and tether breakage occurs. However, they all focused on tether tension force, and the tension force is applied to control input directly. It is difficult to impose desired tension force which is needed. The releasing characteristics and construction of releasing mechanism are not considered. Therefore, these coordinated methods are theoretical and ideal methods.

In this paper, we proposed motor torque control to instead tension force as input, which can be easily imposed by the releasing motor. After the 6-DOF dynamics modeling, a coordinated coupling position and attitude control scheme is designed by combining the releasing motor and thrusters of operation robot. All of these are the highlights of this paper.