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Coupling dynamics modelling and optimal coordinated control of tethered space robot

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ABSTRACT

Tethered space robots use tethers to replace rigid arms and have more flexibility than a traditional space robot, which gives it wide application prospect in future on-orbit servicing missions. Before carrying out elaborate manipulations, tethered operation robots need to approach the target. In order to save fuel in the approaching phase, various coordinated control methods that employ tethers and thrusters together are investigated in the literature. However, the increasing mass of the tether and the distributed force acting on the tether will affect the position and attitude of the robot, which is neglected in previous studies and can degrade the performance of the control system. Here, in order to involve these factors, coupled dynamics and coordinated control theories are combined and applied. Firstly, a coupling dynamics model for the tethered space robot system is built based on the Hamilton principle and the linear assumption. Then, based on the dynamics model, we design an optimal coordinated controller which can minimize the fuel consumption by using the hp-adaptive pseudospectral method and the classical PD controller. Finally, the advantages of the proposed method and the performance of the designed controller are validated by the numerical simulation.

1. Introduction

Large spacecraft is of high value for any country. However, restricted fuel supplies limit their life spans. Sometimes the accidental failure of a small component can also lead to the malfunction of the whole system and greatly shorten the life of these precious spacecrafts [34]. In addition, the soaring of orbit debris is posing an increasing threat on the safety of large space structures [13]. Therefore, many countries and organizations have been researching and developing the on-orbit servicing technologies, including repairing, upgrading, refueling and re-orbiting spacecraft [7,9]. These technologies can potentially extend the life of satellites, enhance the capability of space systems, reduce operation costs, and clean up the space debris. NASA has used the Shuttle Remote Manipulator System installed on the space shuttle to manually capture free-flying satellites and handle them in the payload bay for many times [15]. Perhaps, the best known satellite servicing missions in the human spaceflight program are the periodic missions to service the Hubble Space Telescope [12]. In the Orbital Express mission, NASA further demonstrated autonomous capture of a fully unconstrained free-flying client satellite, autonomous transfer of a functional battery ORU (Orbit Replacement Unit) between the spacecraft, and autonomous transfer of a functional computer ORU with a robotic arm installed on the servicing satellite [24]. In the Engineering Test Satellite VII mission, NASDA also demonstrated a number of autonomous satellite servicing and space robotic manipulator techniques on-orbit [25,35].

Despite these successful applications, the traditional structure, consisting of a space platform and multi-freedom rigid manipulators, still has many limitations in future on-orbit servicing missions, especially in the operation of non-cooperation targets, such as the malfunctioning satellites on the geostationary orbit. This is mainly because the rigid structure has a small range of operation and a high risk of collision, no matter what kind of new materials will be employed in the future. In order to overcome these two shortcomings, the idea to use the tethered space robot which replaces rigid arms with flexible tethers is proposed in projects, such as the Robotic Geostationary Orbit Restorer plan launched by the ESA [6]. Due to the flexible and lightweight characters of the tether, this new structure, as shown in Fig. 1, can not only significantly increase the operational range and therefore avoid the close-range approaching manoeuvre of the space platform, but also prevent the transmission of the terminal collision force towards

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the space platform, which greatly improves the security of the platform [14].

Before performing the intended on-orbit servicing mission, the operation robot should arrive at an appointed position in the neighborhood area of the target and maintain a stable relative attitude. Therefore, how to control the tethered robot system to approach the target and maintain the attitude is one of the key techniques of this system. Considering the extremely light weight and small volume of the terminal operation robot, the limited fuel is very precious and consequently, the cost of fuel is regarded as the most important factor when designing the controller of position and attitude. In order to minimize the fuel consumption in the approaching process, various coordinated controllers that use the deploying velocity or the tension of the tether and the thrust on the operation robot as control variables are investigated in the literature.

The concept of tethered space robot was first introduced by Masahiro who also proposed a casting strategy and an appropriate trajectory adjusting approach by moving the tether attachment point in his paper [20]. Furthermore, he considered the attitude control of the terminal operation robot through moving links with the tether and verified the designed controller by experiments [19]. Nevertheless, in order to simplify problems, he limited the length of the tether to be very short and assumed the tether to be a massless rod in his studies. Yuya discussed the collaborative control of the position of the operation robot in the approaching phase with the tension in the tether and the thrust acting on the robot, whereas the attitude of the robot was not included [36]. Mori adopted the same assumption as Masahiro and established a coordinated controller which used tether tension and thrust, when considering the tethered satellite cluster systems. He demonstrated that the proposed controller could decrease the fuel consumption and improved control precision [26]. Godard also used the same assumption as Masahiro and established a coordinated fault-tolerant nonlinear control frame to control the attitude of a satellite through moving the tether attachment point [11]. Besides, linear optimal control theory based on the application of the linear quadratic regulator (LQR) method was applied by Bainum and Kumar [2]. Williams presented a novel methodology for deployment and retrieval optimization of a multi-body model of two-body Tethered Satellites System, where the tether was modeled as an inelastic but flexible element [32]. Wen et al. designed the optimal control scheme for the deployment of a tethered terminal device based on real-time trajectory generation with online grid adaptation [29] and differential inclusion of the second order with fixed end-time [30]. Besides the traditional control scheme for the Tethered Satellites System, there are some novel control schemes proposed in recent years. Wang and Huang proposed a coordinate control scheme strategy of tethered space robot using mobile tether attachment point in approaching phase and post-capture phase [8,21]. Meng et al. proposed an effective approach coordinate control scheme for the Tethered Space Robot System, in which the tether tension, thrusters and the reaction wheel are all utilized [27]. Even though the tether was involved in these studies, they all assumed it to be a massless rod and neglected the distributed mass of the tether and the force acting on the tether. Besides, they only considered one aspect of orbit and attitude control. In the actual process, the distributed mass of the tether and the distributed force acting on the tether will remarkably degrade the precision of the coordinate controller, especially when the tether's mass is close to or heavier than the mass of the operation robot. Meanwhile, the coupling between the attitude and the position resulting from the tether is likely to cause a great disturbing force, which will lead to the sharp increase in fuel consumption and even the divergence of the whole system.

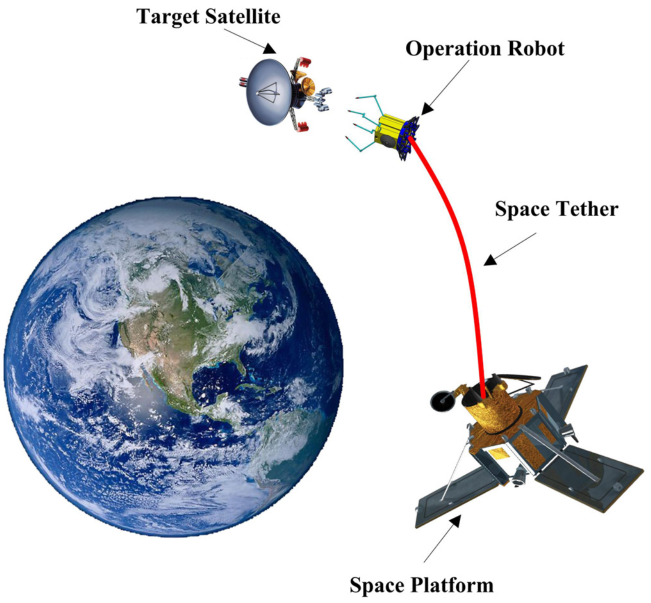

Fig. 1. Structure of the tethered space robot system.

In order to overcome the deficiencies of the controllers proposed in the literature, the massless rod model should be improved at first, and the new dynamics model should consider the attitude, the position of the operation robot, the distributed mass of the tether and the distributed force acting on the tether simultaneously. This needs to refer to the classical methods used in the dynamics modelling of tethered satellites. Presently, there are mainly four kinds of dynamics models for tethered satellites: (1) the rod model, (2) the classic cable theory model, (3) the lumped mass model, (4) the beam model. The rod model converts the stretched tether into an equivalent rod. Since the space tether usually needs to keep certain tension, this simplification is reasonable in most cases and is widely used in the control of tethered satellites. Besides, according to the different application conditions, the model also has different forms. Anderson completely neglected the flexibility and mass of the tether in the drift control of geostationary tethered satellites [1]. Misra considered the effects of varying tether mass by introducing the equivalent system mass [22]. Williams further took the flexibility of tether into consideration when controlling the long tether to capture in-plane payload [31]. However, these models all regard the operation robot as a mass point. This is not suitable for the tethered space robot system, because the operation robot usually needs to adjust its attitude when approaching targets. The classic cable theory model uses dynamics equations of the flexible string to describe the 3-D movement of the space tether, and also assume the operation robot to be a mass point [4]. The lumped mass model discretizes the continuum tether into a series of mass points that are connected by massless flexible rods [3,23]. This model can be used to simulate the dynamical behavior of tethered systems, but it is too complex to be used in the controller design of the deploying tethered space robot. The beam model is a natural extension of the classic cable theory. Compared with the lumped mass model, it has a sound theoretical foundation and physical meaning, which makes it widely used in recent years [18]. It usually employs the Hamilton principle to build the complete system dynamic model at first, and then uses the Ritz method, the Galerkin method or the Finite Element Method to discretize the continuum tether [16,28,37]. This method can precisely calculate the motion of tethered systems, but discretizing the tether with high order functions or dividing it into many segments will also be too complex for getting a model which needs to be used in the controller design.