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Robust distributed consensus for deployment of Tethered Space Net Robot

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A B S T R A C T

The Tethered Space Net Robot (TSNR) is an effective solution for active space debris capture and removal. The opening area of the net during deployment is vital, because the net may shrink or intertwine during deployment due to the shooting error or unknown disturbances. To solve the problem of net shape maintenance, a robust distributed coordination control scheme based on an adaptive law is proposed for the TSNR in this paper. By employing the Lyapunov approach and graph theory, it is proved that position tracking errors of the Maneuverable Units (MUs) in the presence of the bounded disturbance are uniformly ultimately bounded. The simulation results show that the MUs can simultaneously track the desired trajectories steadily and effectively, and the TSNR can keep in a capture-available shape with symmetric and asymmetric configurations.

1. Introduction

Even since the continuous exploration in space, a large quantity of satellites have been spectacularly launched. Inevitably, the number of the space debris is growing as well [1]. The human living space is threatened by space debris [2]. Thus, many space debris capturing systems have been addressed and designed in recent years [3]. Space tethers have attracted much attention in debris capture [4], for example, the Tethered Space Net [5], the Tethered Space Gripper [5], the Tethered Space Robot [6,7] and the Tethered Harpoon [8]. The Tethered Space Net Robot system (TSNR) (Fig. 1) was first proposed in [9], which is used to capture and remove the space debris actively. The TSNR inherits the maneuverability from the Tethered Space Robot (TSR) and compatibility from the Tethered Space Net (TSN). To achieve the maneuverability, the masses at the corners of the TSN are substituted by the Maneuverable Units (MUs). In this case, both trajectories of the MUs and shape of the net can be controlled.

The dynamics modeling and analysis of the TSNR are similar to the TSN, so a brief literature review of the TSN is given as follows. The deployments with different shooting conditions were studied in [10]. Besides the shooting conditions, the characteristics of the net also have significant influence on the deployment, such as the bending stiffness of the net [11]. In [12], the deployment and contact dynamics was described by a multi-body dynamics simulator which has a contribution to the GNC (Guidance, Navigation, and Control) and the net design. The contact dynamics, which plays a vital role in implementation of Active Debris Removal (ADR), has been subject to considerable research. An impact algorithm was proposed in [13] which was verified by the simulation and experiment. Botta et al. established different contact dynamics models by employing the different contact force models, with simulation to compare the effects of different contact dynamics models [14]. To be valid, some experiments on ground have been carried out. In [15], the net parameters were designed by the deployment and wrapping simulation, which was further evaluated by a parabolic flight experiment. To validate the feasibility of the TSN, this parabolic flight experiment on ground were detailed in [16,17].

However, TSNR features the ability to maintain the net configuration, which distinguishes TSNR from the traditional TSN. With the optimal initial velocity of the corner masses, the net of TSN may shrink or even intertwine due to the initial ejection error and environmental disturbance. This undesired configuration can be avoided by controlling the MUs of TSNR. Huang et al. [18] introduced a kind of coordinated control scheme. The simulation results show that the TSNR can move along the desired trajectory and maintain a capture-available shape. Meng et al. [19] designed a dual-loop control strategy for the shape maintenance of the net, including a pseudo dynamic inversion controller and a traditional sliding mode controller. With a disturbance on the TSNR, Zhang

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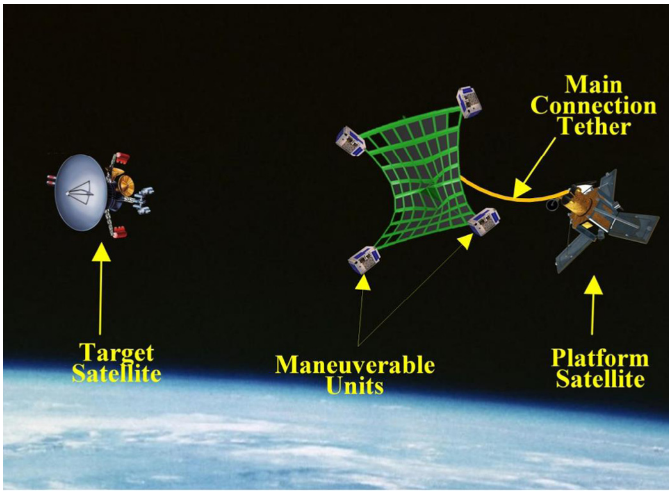

Fig. 1. Tethered space net robot system.

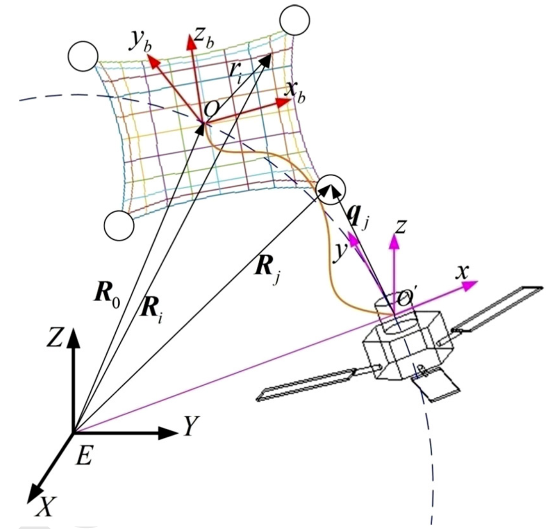

Fig. 2. Schematic representation of coordinate frames.

et al. [20] proposed an adaptive super-twist sliding mode control strategy for the shape maintenance of the TSNR, and verified that TSNR can fly toward target with the symmetric configuration of net deployment. To consider the more general case [21], a modified adaptive super-twist sliding mode controller was designed for symmetric and asymmetric configurations, which has the strong robustness to the disturbance on the TSNR and shooting error on the MUs.

However, all of the literature mentioned above work on the controllers' design without information exchange between the MUs for the TSNR. The TSNR is a typical distributed system with the requirement of synchronization of multi-agent (the Maneuverable Units). Meanwhile, the configurations of the communication subsystem and the sensor subsystem of four MUs are different in practical applications. Therefore, these requirements and features necessitate distributed control method for the TSNR.

This paper is aimed at studying the cooperative relative tracking control of four MUs to realize the shape maintenance of the net during deployment. The TSNR is an underactuated nonlinear system with high degree of freedom. The uncontrollable net leads to the disturbances acting on the MUs. To solve this problem, a robustness controller is designed to eliminate the disturbance. The main contributions of this paper can be summarized as follows.

(1) By introducing the neighbor errors and designing the auxiliary variables for the MUs, the Euler–Lagrange systems are reduced to first-order systems about the auxiliary variables.
(2) Further, a distributed coordination control scheme is designed for the MUs by employing the behavior-based control strategy and consensus algorithms in this paper. The simulation results show that the distributed control strategy is effective on the maintenance control for the shape of the net.

The organization of the paper is stated as follows. In section 2, the system dynamics of the MUs and the flexible net are described. In section 3, the propaedeutics about graph theory are introduced and the controller is designed. In section 4, the stability of the control scheme is analyzed and it is proved that the position tracking errors of the MUs are uniformly ultimately bounded. In section 5, numerical simulations are presented to show the effectiveness of the proposed control scheme. Finally, concluding remarks are given in section 6.

2. Dynamics modeling

Tethered Space Net Robot system is a novel space robot system, which is composed of a platform satellite, main connection tether, a flexible net and four corner MUs, as shown in Fig. 1. Further, the structure of the TSNR and the typical mission scenario are introduced intensively in [20]. Four MUs are regarded as mass points corresponding to the four corners of the flexible net. The lightweight main connection tether is slack during the approaching phase. For this reason, it is logical to ignore the effect of the main connection tether on the flexible net. Assume that the center of mass of the platform satellite lies on an ideal circular Keplerian orbit.

The coordinate frames for the TSNR system are shown in Fig. 2. The inertial frame E_XYZ has its origin E located at the center of the Earth, with its Z axis along the equatorial plane normal toward the celestial north pole. Its X axis is directed toward the vernal equinox and the Y axis represents the third axis of right-handed orthogonal frame. The orbital coordinate frame O'_xyz has its origin O' located at the mass center of the platform satellite, with its x axis outward from the Earth center along the local vertical. Its z axis is directed toward the orbit normal direction and the y axis along the local horizontal represents the third axis of right-handed orthogonal frame. Relative to the platform satellite, there is only translation but no rotational motion for the flexible net. So the body-fixed frame $O\_x_b y_b z_b$ with origin at the center of mass of the flexible net is parallel to the orbital coordinate frame.

The mass-spring model is a widely used method to model the flexible net for its effectiveness and fast calculation [10,22]. Therefore, the mass-spring model is utilized to establish the dynamic model of the flexible net in this research. As shown in Fig. 3, the side of a mesh is called the knit cable. L is the side length of the flexible net. The mass-spring modeling method for flexible net is a kind of simplified modeling method by lumping mass of a knit cable between two interaction knots at the ends of knit cable, and the knit cables are abstracted as massless spring-damper elements. Based on the nature of the cable material, the tension-strain $\boldsymbol{T}_{ij}$ between nodes i and j can be written as

$$\boldsymbol{T}_{ij} = \begin{cases} (\frac{EA}{l_0}(r_{ij} - l_0) + \zeta \dot{r}_{ij})\hat{\boldsymbol{r}}_{ij} & r_{ij} > l_0 \\ 0 & r_{ij} \le l_0 \end{cases} \tag{1}$$

where the notation E represents the Young's modulus of the elastic cable material, A is the cross section of the knit cable, l_0 repre-

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