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Observer-based control for the platform of a tethered space robot

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Abstract This paper addresses the attitude control problem of a space tethered robot platform in the presence of unknown external disturbance caused by a connecting elastic tether. The tether-generated unknown disturbance leads to tremendous challenges for attitude control of the platform. In this work, the perturbed attitude dynamics of the platform are derived with a consideration of the libration of the elastic tether, and then with the purpose of compensating the unknown disturbance, major attention is dedicated to develop a nonlinear disturbance observer based on gyros measurements, after which, an adaptive attitude scheme is proposed by combining the disturbance observer with a sliding mode controller. Finally, benefits from the observer based on an adaptive controller are validated by series of numerical simulations.

1. Introduction

Recently, the fast increment of debris in Earth's orbit has received significant attentions. Evaluation on the orbital environment indicates that large space debris, such as non-functional satellites and upper stages, are ensured to impose the most serious impact to the orbit environment in the near future. With the purpose of suppressing the rapid growth of the debris population, different types of space robot systems are proposed for debris capture and removal. Lots of previous work in this field is focused on space robots with manipulators,[1–5] while other researchers[6,7] have proposed tethered space robots (TSRs) for large-size debris capture and removal. A TSR system is commonly composed of a maneuverable platform and a tether-connected net/gripper. Compared with a manipulator-based space robot system, a TSR achieves potential advantages due to its enhanced error tolerance, increasing capturing distance, and reliable safety.

There are many challenges arise from TSR practical implementation, one of which is the control problem for the post-capture system. Generally, the dynamic behaviors of a post-capture TSR are very similar to those of a typical tethered satellite system. Tethered satellites have been extensively studied in the past decades under the mass point and inelastic tether assumption. The dumbbell model is widely used to describe the tether libration within a local vertical local

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horizontal frame. For example, based on the dumbbell model, Williams[8] investigated the dynamics and control problem for a tethered system in an elliptical orbit, and his work indicates that certain combinations of parameters may lead to a tether slack. Motivated by the potential application for orbital transportation, Lorenzini[9] studied the problem of target rendezvous with a tether tip. To facilitate the relative motion analysis between the tether tip and a target, Takeichi et al.[10] extended his work to find a periodic solution of the tether librational motion in an elliptic orbit. Wen et al.[11–13] also studied the deployment and retrieval control problem based on tether tension regulation. Liu et al.[14] also extended the previous work to a tether satellite in a halo orbit, and a nonlinear output tracking control scheme based on the $\theta - D$ technique was proposed for system station-keeping control.

Due to the weakness of the dumbbell model, many researchers have tried to develop the detailed dynamics of a TSR by taking into account the tether elasticity. However, under the tether elasticity consideration, the longitudinal vibration of high frequency on a connecting tether makes the control problem even more challenging. With the efforts to guarantee TSR safeties, many researchers have dedicated their work to control techniques for the post-capture system. In order to avoid possible collisions between captured debris and the platform, Okazaki and Ohtsuka[15] developed a switching control scheme, and the safety insurance conditions for the post-capture TSR were analytically derived; finally, a satisfactory performance of the safety control scheme was validated by numerical simulations. By using Lagrangian theorem, Aslanov and Yudintsev[16] studied the dynamics of a post-capture TSR before a space tug, in which the influences from debris initial conditions and dynamic parameters, such as debris tumbling, tether elasticity, and thruster accelerations, were investigated and numerically demonstrated. With considerations of system uncertainties, Cleary and William[17] developed a wave-based control method to cope with the post-capture system, and this control scheme is easy to implement in practice due to its less relative measurement requirement. Huang et al.[18–20] presented a robust adaptive back-stepping controller to stabilize a tether-connected debris-gripper combination, and based on utilization of the auxiliary design and the optimal control scheme, the proposed controller effectively reduced possibilities of thruster saturation.

As well as guaranteeing system safety, platform attitude stabilization is also an important aspect for the post-capture system. In particular, the post-capture TSR is required to perform orbital maneuvers for debris removal. However, during the maneuvers, since attitude misalignment evidently leads to a remarkable increment on fuel consumptions, the attitude of the platform should be stabilized precisely with respect to the given reference. However, the tether-generated disturbance, which includes both long-term libration and elastic vibration, greatly increases the difficulties of platform stabilization. In the early 1990s, optimal control based on an integral linear quadratic regulator[21] (LQR) was proposed to suppress the resonances on flexible spacecraft, but LQR applications are very limited due to its dependency on accurate dynamic models. To cope with unknown external disturbances, robust attitude control techniques have attracted much attention in recent years. One of the robust attitude control methodologies is the observer-based control technique, which estimates external unknown disturbances based on necessary measurements for feed forward compensation. By incorporating a disturbance observer into the control loop, Yan and Wu[22] proposed a robust composited attitude control scheme for flexible spacecraft stabilization. Lee[23] addressed the problem of relative attitude control between two spacecraft subjected to an unknown disturbance, and a disturbance observer was also used to enhance the control performance. Liu et al.[24] also proposed a composite controller by combining a disturbance observer with a PD controller for attitude stabilization and vibration reduction of flexible spacecraft, and similar contributions are also available in the literature.[25,26] However, in the above mentioned works, an unknown disturbance is supposed to be slow time-varying, and sometimes approximately treated as a constant; therefore, for the case of disturbance with components of high frequency, perhaps the control performance will be greatly degraded.

In this paper, in order to enhance the attitude stabilization performance for a post-capture TSR platform, an adaptive controller is developed by combining a disturbance observer with a sliding mode controller to reject a disturbance from the elastic tether libration. Major attentions are dedicated to develop a nonlinear disturbance observer which only depends on gyros measurements. In comparison with the works in literature[23,24], the proposed disturbance observer in this paper also works robustly in case of arbitrary time-varying disturbance, and meanwhile, the sliding mode controller in the control loop accounts for the residual disturbance after feed forward compensation. Finally, the benefits from the adaptive controller are analyzed and validated by numerical simulations.

2. Perturbed attitude dynamics of the platform of a TSR

2.1. System description

As shown in Fig. 1, the TSR system under consideration is composed of a platform and debris of mass m connected by a straight massless tether, which is only capable of exerting force along the straight line connecting the debris. The debris is considered as a passive object without any active control. The tether's unstrained length and longitudinal stiffness are l and EA, respectively. When the system operates in its orbit,

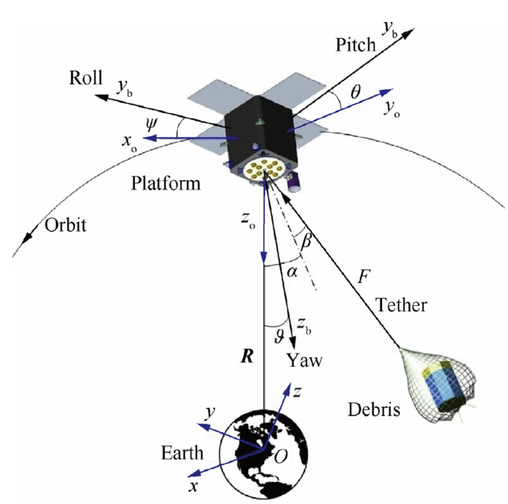

Fig. 1 Illustration of a Post-capture TSR system.

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