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Nonlinear control of sway in a tethered satellite system via attitude control of the main satellite

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ABSTRACT

In this study a new nonlinear control approach is introduced to suppress libration of a tethered satellite system (TSS). It benefits from coupling between satellites and tether libration dynamics. The control concept uses the main satellite attitude maneuvers to suppress librational motion of the tether. To achieve this goal, the main satellite attitude control actuators are used as the only actuation in the system. The study considers planar motion of a two body TSS system in a circular orbit. Governing dynamic equations of motion are derived using extended Lagrange method. Controllability of the system about equilibrium state is studied and a nonlinear controller is designed using feedback linearization method to regulate libration of the system. By studying the conditions of feedback linearization method, stability of the controller is also proved. Tether tension and satellite attitude are assumed as only measurable outputs of the system. The Extended Kalman Filter (EKF) is used to estimate states of the system to be used as the feedback to the controller. By implementing the controller and observer on the system, simulations demonstrate that the controller lead to reduction of the tether libration from large amplitudes.

1. Introduction

The concept of Tethered satellite systems (TSS) has been introduced by Tsiollovsky in 1895 for the first time. In recent decades the idea of connecting satellites with tether has attracted attention of many researchers. Numerous missions have been conducted to examine concepts of these systems [1]. Possible applications of these systems include: scientific experiments like gravity gradient, provision of desired microgravity environment, generation of electricity, space interferometry and remote sensing, deorbiting, deployment of payloads into new orbits, retrieval of satellites for reusing, and etc. [2–6].

General form of TSS dynamics is very complicated which is governed by a set of ordinary and partial nonlinear, non-autonomous and coupled equations. A complete review of recent works on dynamics and control of these systems is presented in [1,7–10].

A typical TSS mission involves deployment, station-keeping, and retrieval phases. There is a broad literature in controlling the motion of TSS in these phases [2,11–16]. Deployment phase is the first and indispensable phase of the mission which is inherently stable provided that certain deployment speeds are not exceeded [16]. In [14–18] various controlling methods in deployment phase are discussed. The next phase is station keeping. Controlling tether in the direction of nadir during this phase is one of the most interested missions in TSS applications. Many studies have been conducted to reach this goal by using various actuators and control methods. Thrusters on satellites [19–21], tether tension control [22], tether rate control, and attachment point position control [10] are among the methods that are used to reduce the librational motion of tether. The last possible phase is retrieval which is known to be unstable. Different controlling schemes have been also developed for stable retrieving of tethered satellites [16,23–26].

From the dynamical view point, tether and satellites dynamics are coupled. To study this, it is necessary to model satellites as a rigid body. In [27] abstract form of the equations of motion for multibody TSS in a three dimensional Keplerian orbit are derived. In this model, satellites are free to undergo three dimensional attitude motions. In [28] oscillation of the main satellite due to tether effects is studied, but it is assumed that the mass of subsatellite, i.e. the satellite which is attached to the main satellite through a tether, is negligible. So center of gravity of the whole system is approximated with the center of gravity of the main satellite. In [29] the effects of the tether on satellite have been modeled with a perturbation force.

In all methods that have been implemented to control libration of a TSS in station keeping phase, it is required to utilize special set of actuation system on satellites to change the length, rate, an-

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Nomenclature

$\mathbf{A_1}$	A nonlinear function vector	T_{Orbit}	Period of orbit
$\mathbf{A_2}$	A nonlinear function vector	$U_{Gravity}$	Potential energy of the system
$\mathbf{A_3}$	A nonlinear function vector	u	Control signal
a_{ij}	Coefficients of Lagrange multipliers	V	Lyapunov function
$\mathbf{C}$	Nonlinear controllability matrix	$\mathbf{v}(t)$	Measurement noise
d	Distance of satellites center of mass	$\mathbf{v}_1$	Velocity of main satellite
d_1	Distance of main satellite from origin	$\mathbf{v}_2$	Velocity of sub satellite
d_2	Distance of sub satellite from origin	$\mathbf{w}(t)$	Modeling noise
$\mathbf{F}$	State transition matrix	$\mathbf{x}$	State vector of the system
$\mathbf{f}$	State function of state space representation	$\mathbf{x}_d$	Desired state vector of the system
$\mathbf{g}$	Input function of state space representation	$\mathbf{y}$	Output vector of the system
$\mathbf{H}$	Observation matrix	$\mathbf{z}$	New state vector (after diffeomorphism mapping)
$\mathbf{h}$	Input function of state space representation	$\mathbf{z}$	Desired new state vector
I	Main satellite moment of inertia	$\alpha(\mathbf{x})$	A continuous function
K	Kinetic energy of satellite	$\alpha_{ijk}(\mathbf{x})$	Any continuous function
$\mathbf{K}(t)$	Kalman gain	$\beta(\mathbf{x})$	A continuous function
$\mathbf{K_C}$	Linear Controller gain	η	Angle of system with Nadir
L	Lagrangian of the system	θ	Satellite absolute rotation angle
l	Length of tether	λ_i	Lagrange multiplier
m_1	Main satellite mass	ζ	Constant of Integration
m_2	Sub-satellite mass	τ	Net torque acting on main satellite
$\mathbf{P}(t)$	Covariance matrix of EKF	τ_C	Controlling torque acting on main satellite
$\mathbf{Q}(t)$	Modeling noise covariance matrix	τ_d	Disturbing torque acting on main satellite
q_i	Generalized coordinates	ν	Control signal of linear system
$\mathbf{R}(t)$	Measurement noise covariance matrix	φ	Angle of satellite relative to tether
R_{Orbit}	Orbital radius	ω_{Sat}	Absolute angular velocity of satellite
r	Distance of tether junction point from COM	ω	Orbital angular velocity

gle, or tension of the tether. In [30], a new control approach is presented to reduce tether libration just by using attitude control actuators of the main satellite. In this method, attitude maneuver of the main satellite and the dynamic coupling between the main satellite attitude and tether libration are used to suppress libration of the tether. It should be noted that usually the mission of the main satellite is not applicable while it is performing the attitude maneuvers to mitigate tether libration, and it can resume to its main mission after accomplishing this phase. To implement such controlling idea, it is necessary to consider the coupling between rigid body motion of satellite and tether libration. In [30] a linear controller is designed to implement the idea. The designed controller just works for low amplitude librations and becomes unstable for large amplitudes. In this study, we overcome this issue by designing a nonlinear controller and analyzing the stability of the closed loop system.

In this study, station keeping phase of a picosatellite deployed from a microsatellite is considered. 2D dynamic equations of the TSS system are extracted in a circular orbit. The main satellite is modeled as a rigid body and the other one as a point mass. Tether is assumed to be inelastic with constant length with no longitudinal or transverse vibration. Based on the new control approach presented in [30], a nonlinear feedback controller is designed to reduce tether liberation using the main satellite attitude maneuvers. The only actuator of the system is a reaction wheel on the main satellite and there are no other actuators like thruster or etc. The nonlinear controller is designed using Feedback Linearization Method. The designed controller is full state feedback. It means that all states of the system are required to be measured and fed to the controller, but some of them are not feasible to be measured. Therefore, it is necessary to design an observer to estimate them. To do this, an Extended Kalman Filter (EKF) is designed which uses tether tension force and the main satellite attitude to estimate the whole states of the system and feed them back to the controller.

2. Modeling

To design a controller, it is required to model the dynamics of the system. Various methods for dynamic modeling of a tethered system exist, where the tether is considered either elastic or inelastic, satellites are modeled as either rigid body or point mass, orbit is assumed circular or non-circular, and etc. [1]. To maintain the advantage of simplicity required for analysis and controller design, the following assumptions are made:

- Because of disturbances in elliptic orbit which affect the libration of tether [31], the system is assumed to be in a circular orbit to study just the effect of the satellite maneuver on libration.
- To perform tether libration controlling maneuvers, the main satellite is modeled as a rigid body. The subsatellite is modeled with point mass because of its small dimension and mass which diminishes its effect on tether libration.
- Because the typical tether mass for this type of application amount to 0.3 kg km^{-1} [15], it is idealized to be massless.
- In these systems, tether has longitudinal and transverse vibration with low amplitude and high frequency [10]. Because of the low frequency nature of the orbital motions and satellite maneuvers, vibrations of tether will not affect the system. Therefor tether could be assumed inelastic with no vibration.

Geometry of the system is shown in Fig. 1. The origin of the orbit coordinate system is located at the center of gravity of the system which moves on a circular orbit. d is the distance between satellites center of mass. η is angle of d with nadir, θ denotes absolute angle of satellite rotation, and φ is the angle of satellite body with d. It is obvious from the figure that $\theta + \varphi = \eta$. Center of mass of the system is moving in circular orbit with radius of R_{Orbit} and angular velocity of ω_{Orbit}.