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Dynamic analysis and trajectory tracking of a tethered space robot

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ABSTRACT

Dynamic analysis and trajectory tracking of a Tethered Space Robot (TSR) is investigated in this paper. A hybrid controller is used to perform the control task. It consists of two components, the first one deals with librational motion of the tether, while the second one takes care of the manipulator motion. A Nonlinear Model Predictive Control (NMPC) approach is used to control the tether libration; for this purpose, the libration is described by a single degree of freedom and the tether length rate is employed as the input to suppress the librational motion. A modified Computed Torque Method (CTM) is used to control the manipulator motion. The dynamic interaction between the manipulator motion and the librational motion is considered both in the system dynamics and control of the system. Using numerical simulations, performance of the proposed control system is evaluated for end-effector positioning as well as for trajectory tracking for two cases: a Low Earth Orbit (LEO) and the Geostationary Earth Orbit (GEO).

1. Introduction

Robots can be classified according to the environment of application: terrestrial robots, submarine robots and space robots [1]. Space robots have become an integral part of many space missions studies due to their high potential of applications in hazardous conditions existing in space. Because of this, a large number of studies have been conducted in this area. Recently, Boning and Dubowsky [2] investigated the cooperative performance of a team of robots carrying out activities such as assembling very large structures in space. However, performance of robots in accomplishing outer space missions suffers from their limited range of accessibility. It is in part to resolve this limitation that the idea of tethered space robots has been proposed.

A tether is a long cable used to connect two objects in space, such as a space robot to a satellite or two satellites to each other. Tethered Satellite Systems (TSS) have been proposed and studied decades ago. However, using tethers in Tethered Space Robots (TSR) presents new horizons. TSRs benefit from several advantages such as usefulness in transferring equipments and astronauts along the tether, enhancing access to more remote points, reducing the risk of robot-satellite impact, facilitating the inspection and repair of satellites or structures at a significant distance from the spacecraft, and reducing the consumption of fuel. On the other hand, these systems suffer from certain drawbacks as well. The chances of knot formation along the length of the tether, and disorder and chaos in the control system due to the presence of an obstacle between the target point and robot are, some of the problems that may arise as a result of using tether connected robots. Space tethered autonomous robotic satellite (STARS) or mother and daughter satellites [3], tether net space [4] and tethered space manipulator [5] are different types of these tether space robots.

The use of tethers has been studied for more than three decades. Numerous investigations have been conducted in this field addressing various issues. The first study of a tether-connected robotic system in space goes back to the year 1992 [6]. The authors investigated the control of a robot connected by a tether to a mechanical arm installed on a satellite. In the same year, they extended their study to a tethered space robot in the absence of the mechanical arm [7]. Woo and Misra [5] determined possible paths in the system internal configuration space when the start and end points of the end effector of the robot are specified and explored the kinematics and dynamics of the system. Wang et al. [8] studied attitude control and coordinate control of the orbit simultaneously for the system that included a space platform, a tether, and a gripper. The coordinate control mechanism was entrusted with provision of the attitude control torques of the pitch and yaw motions. In [9,10], it is explained that the analysis of the motion of tethered space robots depends on the phases of the system divided into the deployment, approach, capture, and postcapture.

In [11], the mission of tethered space robot has been studied in postcapture phase, and a tumbling tethered space robot–target combination is stabilized by a robust adaptive backstepping

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Nomenclature

a	Position of the center of mass of a link
I	Moment of inertia of links and space structure
K	Controller gain matrix
k	Counter for discrete time in MPC
Rc	Radius of the circular orbital
T	Kinetic energy
T_s	Sampling time
V	Potential energy
x, y	Co-ordinates of the end effector in the Cartesian frame
ℓ	Actual length of the tether
ℓ_0	Nominal length of the tether
n_p	Prediction horizon
α	Librational angle of the tether
θ	Relative rotation of a link
ρ	Tether mass per unit length
τ	Actuating torque
Ω	Angular velocity of the orbital motion

Subscripts

$(\ )_1$	Link 1
$(\ )_2$	Link 2
$(\ )_3$	Space structure
$(\ )_d$	Desired value
$(\ )_e$	End effector
$(\ )_s$	Position of the center of mass of the space structure
$(\ )_\alpha$	Librational motion
$(\ )_\theta$	Links and structure motion
$\overline{(\ )}$	Value at equilibrium configuration

controller. In [12], Huang et al. focused on the coordinate control problem in approaching phase. In contrast to other studies, what is remarkable in this paper is increase in tether mass and the effect of the distributed force of the tether on the position and attitude of the robot, which degraded the performance of the control system. Huang et al. [13] studied an optimal trajectory of an operation robot for approaching target based on multi objective velocity impulse method. The comparison between coordinated control and the traditional thruster control and a sensitivity analysis on initial values of parameters, has been investigated In [14]. In [15], a tethered space manipulator was studied. In this paper, for the sake of requiring control torques to stabilize the target, an attitude control has been designed. Eventually, driving the tethered space manipulator was entrusted with an adaptive sliding mode controller. Zhang et al. [16] investigated the estimation of parameters like mass, inertia moments, etc. of unknown target captured with TSS in the debris remediation mission.

The libration motion of tether creates a disturbance effect on the TSR. A review of the state of the art of the in-plane and out-of-plane librational motion of two-body tethered systems was presented in [17]. Libration control can be implemented for a tethered system by the modulation of the tension in the tether or of the tether reel rate [17,18].

For years, the model predictive control (MPC) has been recognized as a frequently applied control technique for constrained multivariable systems. This method has been formulated in both linear and nonlinear schemes, and it generates the optimum input for the system by a receding horizon [19]. In the late 70's, with the development of constrained optimization problem solvers, the model predictive controller was quite a popular in the field of control engineering. Papon et al. [20] were among the first researchers who proposed this approach for solving control-related problems. In 1982, Chen and Shaw [21] extended the results obtained from the investigation of the stability of MPC based on receding horizon strategy for linear systems to nonlinear systems. Since the mid-20th century, the nonlinear model predictive controller was presented as a solution framework for optimal control problems. By optimizing the investigated index, this approach controls the trajectory tracking problem as adequately as a point-by-point control problem. Mayne et al. [22] indicated that model predictive control (MPC) is commonly used in industrial applications. They also described the implementation procedure of this method for control problems.

In the tethered space robotic system investigated in this paper, the length of the tether is allowed to be varied within a limited range. Therefore, the system constrained and has limitation on its input. It seems that the Model Predictive Control (MPC) method, which is able to solve constrained system problems, can be an appropriate choice to control such systems.

The dynamical model of the system considered in this paper is described in the next section. An introduction to the proposed controller and related control laws, together with the results of simulations, are presented in the third and fourth sections, respectively. Finally, conclusions are presented.

2. Dynamical model

2.1. Description of the system

The system under study consists of a main satellite and a two link manipulator which is attached to the main satellite via a tether of length ℓ (Fig. 1). The main satellite orbits the Earth in a circular orbit of radius R_c. A robotic arm is used to move the structure S in space. In order to analyze the system dynamics and design a controller for the system, it is assumed here that the motion of the system takes place entirely in the orbital plane and as far as the control of end effector is concerned the length of the deployed tether is almost constant and it only varies within a limited range. It is also assumed that the structure and the robot are totally rigid and that the motion of the main satellite is not affected by the tethered system and maintains its orbital motion. Lengths of the first and second links are indicated by ℓ_1 and ℓ_2, and the distance of their centers of mass from their proximal joints are denoted by a_1 and a_2, respectively. Also, to simplify the analysis, the structure is modeled as a rod of length ℓ_3, which is carried by the end effector at its midpoint. In this analysis, it is assumed that the structure is grasped by the end effector.

The complete dynamics of the system is described by means of variables α, θ_1, θ_2, θ_3 and ℓ, where θ_1, θ_2 and θ_3 indicate the rotations of the joints of the mechanical arm and structure, and α describes the libration of the tether from the local vertical axis about the orbit normal. The mechanical arm is controlled by the applied torques τ_1 and τ_2, and the structure's rotational motion is controlled by torque τ_3. Librational motion of the tether is usually controlled by one of these two methods: controlling the length of the tether, or controlling the tension in the tether. In this paper, the former has been employed. To achieve this objective, a pulley installed in the main satellite is utilized. In view of the above statements,$q^T = \left[\alpha, \theta_1, \theta_2, \theta_3\right]$ are used as the generalized coordinates of the system and $u = \dot{\ell}/\ell, \tau = [\tau_1, \tau_2, \tau_3]^T$ are used as the system's control inputs.