Aerospace Science and Technology 51 (2016) 171–180

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Attitude takeover control for post-capture of target spacecraft using space robot

Panfeng Huang[a,b,*], Ming Wang[a,b,c], Zhongjie Meng[a,b], Fan Zhang[a,b], Zhengxiong Liu[a,b]

[a] National Key Laboratory of Aerospace Flight Dynamics, Northwestern Polytechnical University, Xi'an 710072, China
[b] Research Center for Intelligent Robotics, School of Astronautics, Northwestern Polytechnical University, Xi'an 710072, China
[c] North Automatic Control Technology Institute, Taiyuan 030006, China

ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form 23 November 2015
Accepted 7 February 2016
Available online 10 February 2016

Keywords:
Attitude control
Takeover control
Post-capture
Space robot
Spacecraft
Control allocation

ABSTRACT

When the spacecraft reaches the end of life, its payload will still be able to work in most cases. Due to the loss of attitude control ability, these failed satellites had to be abandoned. The technology of attitude takeover control can be used to extend the operational lifetime of these failed satellites. Post-capture of target spacecraft using space robot will cause a large shift in the dynamics of combined spacecraft. Not only do the mass properties change, but also does the reaction wheels' configuration. Designing a reconfigurable control system can account for these changes. In this paper, a reconfigurable control system is designed for attitude takeover control of target spacecraft, which considers the changes of the mass properties and reaction wheels' configuration. Firstly, a modified SDRE (Sate-Dependent Riccati Equation) optimal controller is proposed to guarantee the convergence of the steady-state position errors and velocity errors, and meanwhile move the closed-loop poles of system in order to provide a sufficient stability margin. Then, a θ–D suboptimal control solving technique is adopted to solve an approximate solution of the modified SDRE optimal controller. Moreover, the control torques of reaction wheels of service spacecraft can be reallocated and satisfy some constraints using the dynamic control allocation method. Numerical simulations validate the feasibility of the reconfigurable control systems with large mass properties changes.

1. Introduction

When the spacecraft reaches the end of life, in most cases its payload will still be able to work. Due to the loss of attitude and orbit control ability, these failed satellites had to be abandoned [1]. However, if the attitude and orbit control ability can be recovered, these satellites will be able to continue to work. The technology of spacecraft takeover control can be used to extend the operational lifetime of these failed satellites [2]. The service spacecraft will take over attitude and orbit control functions of target spacecraft with a surrogate control system, and allow the target spacecraft to operate the other functions as normal [3]. For example, the DEOS [4], CX-OLEV [5]/SMART-OLEV [6] and SUMO/FREND [7] projects focused on capturing and docking geostationary telecommunications satellites, and extending their operational lifetime by supplying them propulsion, navigation and guidance services. For the on-orbit servicing of target spacecraft, which is not designed with custom grappling mechanical interfaces or visual marker, the space manipulator capture using visual servoing is one of the most promising ways [8]. Therefore, one particular scenario for spacecraft takeover control mission is to use the space manipulator mounted on the service spacecraft to capture the liquid apogee engine nozzle or launch vehicle interface ring of target spacecraft [9,10]. Post-capture of target spacecraft using space robot will cause a large shift in the dynamics of combined spacecraft. Not only do the mass properties change, but also does the reaction wheels' configuration. If the mass/inertia ratio of the target spacecraft to the service spacecraft is relatively large, these changes will be very significant. Designing a reconfigurable control system can account for these changes. Therefore, we study the attitude takeover control for post-capture of target spacecraft using space robot.

The capture and post-capture control of space robots as well as the impact and post-impact control of space robots has been well studied. In [11], two types of post-impact dynamics, soft impact and hard impact, were defined based on the relative velocity of end-effector and target. An interesting idea was proposed in [12] on how to use contact/impact to damp the angular momentum of an uncooperative spinning target in order to alleviate the cap-

---

[*] Corresponding author at: National Key Laboratory of Aerospace Flight Dynamics, Northwestern Polytechnical University, Xi'an 710072, China. Tel.: +86 29 88460366x801; fax: +86 29 88460366x803.

E-mail address: pfhuang@nwpu.edu.cn (P. Huang).

http://dx.doi.org/10.1016/j.ast.2016.02.006
1270-9638/

ture mission. In [13,14], the distributed momentum control strategy for capturing a free-floating spinning satellite was presented. The reaction null space motion control was applied to facilitate the pre-impact and post-impact control phases. Yoshida et al. [15] designed a possible control sequence that included the bias momentum approach during the approaching phase, the impedance control during the impact phase and the distributed momentum control during the post-impact phase for a successful capturing operation. Liu et al. [16] derived an impact model to simulate the post-impact dynamics of entire system and designed a proportional derivative controller to maintain the stabilization of robot system after the capture of the object. Flores et al. [17] investigated an optimal control strategy for a space manipulator to provide minimal impact to the base satellite during a capturing operation. Aghili [18] focused on optimal control of space manipulator in the post-capture phase so as to bring the tumbling non-cooperative satellite to rest in minimum time while ensuring that the magnitude of the interaction torque between the manipulator and target remains below a prescribed value. Xu et al. [19] proposed a method for berthing a target and re-orientating the base at the same time, using manipulator motion only after capture. Chau et al. [20] investigated a new algorithm to produce reactionless motion for a space manipulator during and after capture of an unknown uncooperative tumbling target. Abiko et al. [21] designed a control law to accumulate the angular momentum resulting from capture of a tumbling target, in the presence of uncertainty in dynamic parameters of the target. In [22,23], Huang et al. discussed and presented the post-capture attitude control for a tethered space robot–target combination system. Therefore, the capture and post-capture control of spacecraft will become an important research topic on space technology.

Reconfigurable control systems possess the ability to accommodate system failures or re-configuration automatically based upon a priory assumed conditions. Many researches on reconfigurable control systems focus on re-configuration for actuator failure detection and recovery in the aircraft and spacecraft control. Dhayagude et al. [24] proposed a novel linear model following approach for reconfigurable control systems design, where a unique system configuration and design method were employed. Davidson et al. [25] presented the development of an integrated reconfigurable control allocation approach, which combined frequency apportioned control allocation with actuator failure detection and isolation. Furthermore, the reconfigurable control systems have been applied on the multiple spacecraft, the modular spacecrafts and modular space robots for autonomous assembly. In [26], they suggested a complete solution for guidance, navigation, and control of planar multiple spacecraft assembly maneuvers. In [27], they described a novel hybrid-control strategy to reconfigure multi-body spacecraft from one shape to another in such a way that passively stable system dynamics enabled both low control effort and a high degree of robustness. In [28], an optimal control method was used to coordinate the control of the modules after assembly, insure good performance, and best utilize the combined resources of the assembly of modules. In [29], the control of self-assembling space robots was explored in simulations and experiments.

Substantial work has been done on the post-capture control and reconfigurable control system design by many researchers. However, little research exists on attitude takeover control for post-capture of target spacecraft using space robot. Obviously, the reconfigurable control system design is quite challenging and complicated. There are numerous control challenges resulting from changes of mass properties and reaction wheels' configuration, and actuator redundancy, which are not addressed and solved. A modified SDRE (Sate-Dependent Riccati Equation) optimal controller is proposed to guarantee the convergence of the steady-state position errors and velocity errors, and meanwhile move the closed-loop poles of system in order to provide a sufficient stability margin. Then, a θ–D suboptimal control solving technique is adopted to solve an approximate solution of the modified SDRE optimal controller. Moreover, by the dynamic control allocation method, the control torques of reaction wheels of service spacecraft can be re-allocated and satisfy some constraints.

This paper is organized as follows: In Section 2, the attitude error dynamics of combined spacecraft is established in terms of MRP (Modified Rodrigues Parameter). Then, a reconfigurable control system is designed for combined spacecraft in Section 3. The control re-allocation based dynamic control allocation is introduced in Section 4. Furthermore, the feasibility of the reconfigurable control system is validated using a numerical simulation, and the results are presented and analyzed in Section 5. Finally, the conclusions are stated in Section 6.

2. Attitude error dynamics of combined spacecraft

2.1. Problem description

Without loss of generality, we assume that the combined spacecraft system consists of a rigid service spacecraft, a rigid target spacecraft and two rigid space manipulators. The launch vehicle interface ring of target spacecraft is captured using space robot, shown in Fig. 1. In the post-capture phase, the joints of space manipulators would be locked, and the dynamics of combined spacecraft can be represented by the lumped parameter.

Before describing the detailed attitude takeover control in post-capture of target spacecraft using space robot, we define the following assumptions: (A1) There is no attitude control capability for target spacecraft, whose attitude control is taken over by the attitude control system of service spacecraft. (A2) The service spacecraft attitude is driven by four reaction wheels, whose installation locations and directions are known. (A3) The space manipulators cannot change configurations during the attitude control, once the joints of the space manipulators are locked in post-capture of target spacecraft. (A4) The mass properties of service spacecraft, target spacecraft and space manipulator are known or have been identified.

To simplify the description, let us define some frames. The origin of the orbital frame $O x_o y_o z_o$ is located at the centroid of combined spacecraft, the x_o-axis is along the local horizontal direction in the orbital plane, the y_o-axis is along the orbital normal and the z_o-axis is collinear with a line that extends from the center of the earth to the centroid of combined spacecraft and completes a right-handed triad. Similarly, the $O_S x_S y_S z_S$, $O_T x_T y_T z_T$, $O'_C x'_C y'_C z'_C$, and $O_C x_C y_C z_C$ denote respectively the body frame of service spacecraft, the body frame of target spacecraft, the body frame of combined spacecraft, and the inertia principal axis frame of combined spacecraft.

2.2. Attitude dynamics of combined spacecraft

The Modified Rodrigues Parameter (MRP) is adopted to describe the attitude kinematics of combined spacecraft. The kinematics model of combined spacecraft in terms of the MRP takes the following form

$$\dot{\boldsymbol{\sigma}} = \boldsymbol{G}(\boldsymbol{\sigma})\left[\boldsymbol{\omega} + \omega_0 \boldsymbol{R}_2(\boldsymbol{\sigma})\right] \tag{1}$$

where $\boldsymbol{\sigma} = \begin{bmatrix} \sigma_1 & \sigma_2 & \sigma_3 \end{bmatrix}^{\mathrm{T}}$; $\boldsymbol{\omega}$ is the absolute angular velocity of the combination expressed in the inertia frame; ω_0 is orbital angular rate value; $\boldsymbol{R}_2(\boldsymbol{\sigma})$ is the second column-vector of the direction cosine matrix $\boldsymbol{R}(\boldsymbol{\sigma})$

$$\boldsymbol{R}(\boldsymbol{\sigma}) = \boldsymbol{E}_3 - \frac{4(1-\boldsymbol{\sigma}^{\mathrm{T}}\boldsymbol{\sigma})}{(1+\boldsymbol{\sigma}^{\mathrm{T}}\boldsymbol{\sigma})^2}\boldsymbol{\sigma}^{\times} + \frac{8}{(1+\boldsymbol{\sigma}^{\mathrm{T}}\boldsymbol{\sigma})^2}\left(\boldsymbol{\sigma}^{\times}\right)^2 \quad \text{and}$$