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ScienceDirect

Advances in Space Research xxx (2016) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

# Passivity-based control with collision avoidance for a hub-beam spacecraft

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Received 27 March 2016; received in revised form 8 August 2016; accepted 13 September 2016

**Abstract**

For the application of robotically assembling large space structures, a feedback control law is synthesized for transitional and rotational maneuvers of a 'tug' spacecraft in order to transport a flexible element to a desired position without colliding with other space bodies. The flexible element is treated as a long beam clamped to the 'tug' spacecraft modelled as a rigid hub. First, the physical property of passivity of Euler-Lagrange system is exploited to design the position and attitude controllers by taking a simpler obstacle-free control problem into account. To reduce sensing and actuating requirements, the vibration modes of the beam appendage are supposed to be not directly measured and actuated on. Besides, the requirements of measuring velocities are removed with the aid of a dynamic extension technique. Second, the bounding boxes in the form of super-quadric surfaces are exploited to enclose the maximal extents of the obstacles and the hub-beam spacecraft. The collision avoidance between bounding boxes is achieved by applying additional repulsive force and torque to the spacecraft based on the method of artificial potential field. Finally, the effectiveness of proposed control scheme is numerically demonstrated via case studies.


*Keywords:* On-orbit assembly; Passivity-based control; Velocity-free; Super-quadrics; Collision avoidance

## 1. Introduction

Extremely Large Space Structures (LSSs), such as space solar power plants and large-aperture space telescopes, have a great potential for future developments in space science and engineering (Lillie, 2006; Whittaker et al., 2001). These space systems are too large to be launched as a single monolithic structure since their excessive sizes are far beyond the volume limits of launch vehicle capabilities. In addition, conventional deployable designs may be also impracticable for the construction of such LSSs, due to the ultimate bottleneck arising from their significantly increased complexity with size (Doggett, 2002).

Autonomous assembly using robotic spacecrafts has been identified as a promising technology for on-orbit construction of future LSSs. For example, Whittaker et al. (2001) made a conceptual study on autonomous assembly, inspection, and maintenance of space solar-power facilities using a team of space robots which consist of free-flying robots, fixed-base manipulators, and attached mobile manipulators, etc. Lillie (2006) presented the mission concepts and conceptual designs for the on-orbit assembly and the subsequent on-orbit servicing of future space observatories. Izzo et al. (2005) investigated the feasibility of transferring reflector elements using the solar flux to the construction site from a lower orbit and then assem-

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http://dx.doi.org/10.1016/j.asr.2016.09.013
0273-1177/

Please cite this article in press as: Wen, H., et al. Passivity-based control with collision avoidance for a hub-beam spacecraft. Adv. Space Res. (2016), http://dx.doi.org/10.1016/j.asr.2016.09.013

bling the large reflector from the elements. Miller et al. (2008) proposed a hardware-in-the-loop testing program, called Assembly of a Large Modular Optical Telescope (ALMOST), for demonstrating in-space robotic assembly of precision, potentially flexible structures under micro-gravity conditions. Underwood et al. (2015) presented a low-cost mission, based on CubeSat/micro-satellite technology, for demonstrating all the key technological steps needed for the Autonomous Assembly of a Reconfigurable Space Telescope (AAReST) using multiple mirror elements.

Despite of their appealing features, the robotic assembly of any flexible LSS will give rise to many challenging problems. First, the translational and rotational motions coupled in spacecraft proximity maneuvers have to be taken into consideration for implementing in-space robotic assembly. Considerable efforts have been made to develop the translation and attitude control laws for spacecraft proximity maneuvers. For example, Filipe and Tsiotras designed a nonlinear adaptive position and attitude-tracking controller based on the dual quaternions for proximity operations between a target and a chaser satellite (Filipe and Tsiotras, 2015). Sun and Huo presented a series of investigations on the adaptive control of the proximity operations for spacecraft rendezvous and docking with the consideration of the dynamic coupling between relative translation and rotation, parametric uncertainties, external disturbances, thrust misalignment, and gravity effect (Sun and Huo, 2015a, 2015b, 2015c, 2016). Gui and Vukovich combined a PD controller with an adaptive algorithm for the simultaneous attitude and position tracking of a rigid spacecraft based on dual quaternion description (Gui and Vukovich, 2016). Second, autonomous collision avoidance is of crucial importance for the robotic assembly involving proximity maneuvers (Badawy and McInnes, 2008; Okasha et al., 2015). The studies on the collision avoidance problem of spacecraft have been usually based on the rigid-body models for two possibly colliding objects. Among them, most of studies did not account for the shape of spacecraft, but only the shape of the obstacle, or just used the distance between the geometrical centers of obstacle and spacecraft to measure their proximity. For example, Richards et al. (2002) presented how to find the optimal trajectories subject to avoidance requirements by formulating the problem as a mixed integer linear program. Okasha et al. (2015) proposed a discrete multi-pulse technique to track the guidance trajectory efficiently while avoiding collisions between satellites during in-orbit-self-assembly proximity operations. There are relatively few studies accounting for the shape of spacecraft. For instance, Badawy and McInnes (2008) presented a method based on superquadric artificial potential fields to achieve the autonomous on-orbit assembly of a LSS. Their approach allows collision avoidance by both translation and rotation so as to achieve more precise maneuvering than the previous approaches using spherically symmetric potential fields.

Another problem of great concern is that robotic operations during the assembly process always cause the elastic deformation and the vibration of structural members, which can hardly be damped out due to the low level of structural damping. Besides, the highly under-actuated nature of the robotic spacecraft carrying flexible elements poses a greatly challenging output-feedback and under-actuated control problem. Hence, great efforts have been made to control the above deformation and vibration concerning autonomous assembly of flexible space structures. For example, Katz et al. (2010) experimentally explored the feasibility of the autonomous assembly of flexible structures using the Self-Assembling Wireless Autonomous Reconfigurable Modules (SWARM) hardware, and demonstrated some key technological steps via ground-based experiments, such as the control of a flexible structure, docking, and reconfiguration after docking. Boning and Dubowsky (2010) presented controller designs and ground-based experiments to demonstrate the concept of using coordinated space robots for autonomously assembling LSSs in orbit, and proposed to control the robot motions and structural vibrations by decoupling the control of the high-frequency robots from that of the low frequency structures. The studies simultaneously accounting for the structural flexibility and the collision avoidance requirement have been relatively rare so far. For instance, with a limited focus on planar motions, Chen et al. (2016) combined a collision avoidance controller and a consensus controller with the output feedback of position and velocity to achieve the assembly mission of a flexible LSS and suppress the vibration of flexible elements.

As a prerequisite for robotically assembling flexible LSSs, small autonomous ‘tug’ spacecrafts are usually required for the transportation of flexible elements to desired positions without colliding with other space bodies. For this purpose, a feedback control law is synthesized in this work for transitional and rotational maneuvers of the ‘tug’ spacecraft carrying a slender flexible element in the space environment with obstacles. The flexible element is modelled as a long beam clamped to the ‘tug’ spacecraft which is actuated on its rigid-body degrees of freedom and modelled as a rigid hub. As an extension of the previous study by Badawy and McInnes (2008), the main contribution of this work is to remove the requirement of velocity measurement in Badawy and McInnes (2008) and take the structural flexibility into account. The design of the controller involves two main steps. Firstly, the physical property of passivity of the system is exploited to design a velocity-free controller from an obstacle-free control problem, where the vibration modes of the appendage are supposed to be not directly measured and actuated on. And then, the collision avoidance is achieved by applying the method of superquadric artificial potential fields (Badawy and McInnes, 2008). Finally, the effectiveness of proposed control scheme is numerically demonstrated via case studies.

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