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Output consensus and collision avoidance of a team of flexible spacecraft for on-orbit autonomous assembly

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ABSTRACT

Multiple spacecraft that work in concert to assemble as a cohesive unit will play an important role in future space missions. In addition, the individual spacecraft trends to be more and more flexible. A typical flexible spacecraft usually consists of a relatively rigid craft body with one or more flexible appendages, which can be reasonably simplified as free-floating hub-beam system and formulated in a floating frame. The formulation of the network of hub-beam systems is a team of Lagrangian systems in essence. In this study, a compound controller which combines an output consensus controller and a collision avoidance controller to a team of hub-beam systems is proposed. To achieve the assembly mission and suppress the vibration of flexible spacecraft appendages, the design of the control law is decomposed into four steps. Firstly, the hub-beam systems in the team are numbered according to specific rules. Secondly, the attitudes of the hubs are regulated to the desired values synchronously. Thirdly, the whole team of hub-beam systems is driven to the pre-assembly states. Fourthly, the team of hub-beam systems is assembled. In the second and the third step, the compound controller is used to actuate the team to the target configuration. In the fourth step, only the output consensus controller is needed. Finally, two case studies are given to verify the effectiveness of the proposed autonomous assembly strategy.

1. Introduction

The technology of on-orbit assembly has been identified as a key requirement for future space missions [1–5] since it may provide an appealing solution to the on-orbit construction of large space structures, including space telescopes, satellite antennas and solar power systems. Because extravehicular activities of astronauts are very expensive and dangerous in practice, it is better to assemble the large space structures via a coordinated team of autonomous space robots or spaceships on orbit [6–8]. The relevant studies have become quite active over the past decades, but most of them have focused on the self-assembly of two or several rigid spacecraft. For example, Badawy and McInnes [9] developed the guidance and control algorithm by using super-quadric artificial potential fields to complete the autonomous on-orbit assembly of a large space structure. Okasha et al. [1] studied the autonomous self-assembly of multiple satellites on orbit in close proximity operations based on the closed-form analytical solution of relative motion equations. Zhang and his colleagues [10] investigated an improved method based on special-point-based maneuvers to realize autonomous rendezvous phasing in a near-circular orbit. Notably, the space structures trend towards larger scale and lighter weight. Hence, Boning and Dubowsky [6] presented a general solution for transporting, manipulating and

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assembling large flexible space structures on orbit via a team of space robots. In other words, the individual in the assembly mission becomes a flexible spacecraft. A classical flexible spacecraft often consists of long flexible appendages, such as antennas and solar panels. Maneuvering of such a spacecraft always causes the dynamic deformations of appendages [11]. The dynamic model of a spacecraft with flexible appendages should, hence, include the interaction between both rigid modes and flexible modes. The spacecraft with a long appendage can be reasonably simplified as a free-floating hub-beam system. It should be noted that the hub-beam system is a Lagrangian system.

The objective of this study is to design a controller for the self-assembly of a team of spacecraft with flexible appendages, which is, in essence, a group of Lagrangian systems. The distributed cooperative control of Lagrangian systems has attracted much attention in control community in recent years because of its advantages, such as greater efficiency, higher robustness, and less communication requirements [12–16]. Nevertheless, most researches have focused on the cooperative control of the positions or the attitudes of rigid bodies or some other simple Lagrangian systems. For instance, Zou [17] presented the distributed attitude synchronization and tracking control for multiple rigid bodies when a common time-varying reference attitude was available to only a subset of the rigid bodies. Meng et al. [18] studied the swarm tracking problem with group dispersion and cohesion behaviors for a group of Lagrange systems. Abdessameud and his colleagues [19] studied the attitude synchronization problem of multiple rigid bodies or spacecraft in the presence of communication delays. Formation flying was the main application of the existing studies on the distributed control for multiple Lagrangian systems [13,16,20]. As stated in [21], few studies were made on the attitude cooperative control for multiple flexible spacecraft.

The cooperative control to the assembly of a team of spacecraft is far different from that to the attitude synchronization or formation flying of a team of spacecraft because the distance between any two spacecraft is very small. A collision avoidance controller, hence, must be involved to complete the assembly. Many collision avoidance strategies have been studied so far. Among them, two major kinds are rule-based approaches and optimization-based approaches [22]. The rule-based approaches include the avoidance strategies of using collision avoidance probabilities [23], the artificial potential field based approaches [24], etc. Compared with other rule-based approaches, the avoidance force from artificial potential field based method is usually available in analytic and continuous form. In the optimization-based approaches [25], the collision avoidance is achieved by adding corresponding constraint conditions and an optimized solution is obtained. For a large team of spacecraft, however, these methods become very complex and can hardly be implemented. Therefore, the collision avoidance method based on artificial potential field is preferred in this study. It can be realized by building a virtual repulsive potential field, the gradient of which, in principle, provides a collision-free path [9,24,26]. This method is easy to be implemented

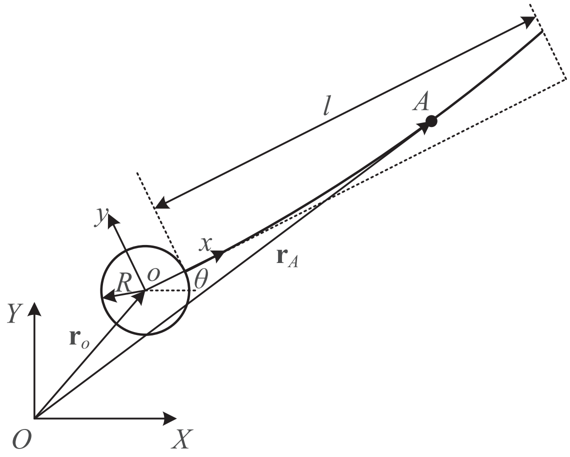

Fig. 1. The kinetic model of a free-floating hub-beam system.

and understood although it may not be optimal in resource or time [27,28].

This study is to make an effort to deal with output consensus of a team of autonomous spacecraft for on-orbit assembly, especially taking the critical issues, i.e. structural flexibility and collision avoidance, into consideration. The rest part of the paper is organized as follows. In Section 2, the dynamic equation of a team of free-floating hub-beam systems is established in the floating frame of reference. In Section 3, an output consensus controller and a collision avoidance controller are designed. In Section 4, the assembly mission is described in four steps. Afterwards, two case studies are given in Section 5 to verify the controller. Finally, the conclusions are drawn in Section 6.

2. Formulations

The spacecraft with a flexible appendage, which can be simplified as a free-floating hub-beam system in Fig. 1, is a widely used model in space engineering. In this study, the dynamic equation of such a spacecraft, modeled as a hub-beam system, is formulated in a floating frame such that the formulation derived is called as Floating Frame of Reference (FFR) formulation [29]. In the FFR formulation, the deformation of a beam should be very small so that it can be superimposed on the rigid-body motion during analysis. As the dynamic equation of the beam is infinitely dimensional by nature, the dynamic equation of the beam has to be truncated to a finite dimensional model via so-called Assumed Mode Method (AMM) [30,31].

2.1. Formulation of an individual hub-beam system

In this study, the zero-th order approximation of coupling dynamics [32] is used. The effect of axial deformation of the beam is ignored. The system is described by two sets of coordinates, i.e., the inertial frame *OXY* and the body frame *oxy*. The coordinate vector of point *o* in frame *OXY* is $\boldsymbol{r}_o = \begin{bmatrix} X_o & Y_o \end{bmatrix}^{\mathrm{T}}$, where X_o and Y_o represent *X*-coordinate and *Y*-coordinate of the center of the hub, respectively, and θ is the attitude angle of the hub. The superscript “T” is the