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Formation control of multi-robots for on-orbit assembly of large solar sails

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ABSTRACT

This study focuses on the formation control of four robots used for the on-orbit construction of a large solar sail. The solar sail under consideration is non-spinning and has a 1 km^2 area. It includes a hub as the central body and four large booms supporting the lightweight films. Four formation operating space robots capable of walking on the boom structure are utilized to deploy the sail films. Because of the large size and mass of the sail, the robots should remain in formation during the sail deployment to avoid dramatic changes in the system properties. In this paper, the formation control issue of the four robots is solved by an adaptive sliding mode controller. A disturbance observer with finite-time convergence is embedded to improve the control performance. The proposed controller is capable of resisting the strong uncertainties in the operation and do not require the accurate parameters of the system. The stability is proven, and numerical simulations are provided to validate the effectiveness of the control strategy.

1. Introduction

Solar sails are a type of propellantless spacecraft driven by the momentum of solar radiation [1]. There has been a renewed interest in solar sailing due to the development of ultra-lightweight sail films and deployable booms. The feasibility of solar sails was demonstrated by the Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS) in May 2010 [2]. This has further encouraged people to utilize solar sails for deep-space missions. A direct solution to make the solar sail capable of carrying more instruments and working as an interplanetary cargo ship is enlarging the area of the sail to obtain adequate acceleration from the sunlight. A 1 km^2 sail is required for carrying a payload on the order of a few tons [3]. Therefore, several studies on how to construct such an ultra-large sail have been conducted. Brown has designed an in-space assembly approach for large solar sails [4] with dimensions up to 1 km. Woo et al. has proposed using formation-flying satellites attached to the tip of the spinning sails to eliminate the sail's supporting structures [5]. However, the former design has a complex mechanism, thus reducing the system reliability, whereas the latter demands high-precision formation control of the tip-satellites to maintain the shape of the sail, and the gas thrusters of the tip-satellites limit the lifetime of the system.

In this paper, we propose using formation operating robots to construct a non-spinning solar sail with an area of several square kilometers. Although the overall system, composed of several robots and the container for the materials of the solar sail, is complex, the produced ultralarge solar sail is rather simple. Furthermore, the space robots can be reused for other tasks, such as constructing the next sail or other on-orbit services.

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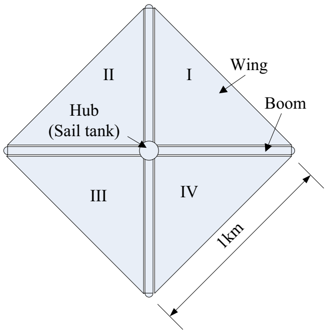

Fig. 1. A non-spinning solar sail.

The considered system (Fig. 1) is comprised of a spacecraft hub containing the folded sail before deployment, four booms as the supporting structure, and four wings in different quadrants. The booms can also be assembled on-orbit by the space robots. Therefore, the length of the boom is not a limitation of the sail size as long as the strength is satisfied. Normally, a mechanical device should be designed to automatically expand the sail [2,5,6]. However, when the sail is several kilometers squared in size, most of the mechanisms, such as the spinning expansion devices [2] and deployable booms [5], are no longer workable due to the large mass of the sail. One effective mechanism that is not influenced by the system size is using on-orbit operating robots to drag the tips of the sails to the desired position, thereby realizing the deployment. Fortunately, space robots have been advanced considerably in recent years [7–10], which has laid a foundation for the on-orbit assembly of a large solar sail. For example, the space robot with multiple manipulators (Fig. 2) designed in Ref. [7] can be adopted. This robot could walk on the boom using two manipulators while a third one holds the sail.

There are three major control issues to be solved to realize the on-orbit assembly of the large solar sail shown in Fig. 1: formation control of the operating robots, joint torque control of each robot to realize the desired trajectory, and attitude control of the large sail during the assembly. The hierarchy of the three control issues is shown in Fig. 3. First, the formation controller should be designed to yield a control force to drive the robot to move along the supporting boom. Second, the single robot control yields the joint torques to realize the desired walking trajectories and speeds, as obtained from the formation control. Third, the sail attitude should remain stable during the assembly process. In this paper, we only focus on the formation control of the robots.

When designing the formation control of the robots for solar sail assembly, the first and second moments of mass of the sail, as well as the environmental torques, such as the solar pressure torque and gravitational torque, will dramatically change during the operation due to the sail's large size and mass (Assuming that the film is made out of aluminum-coated Kapton with a density of 5 g/m^2 and the area of each wing is 0.25 km^2, the mass of each wing will be approximately 1250 kg). Therefore, to avoid additional environmental torques and maintain the system's stable attitude, the four robots should operate in the following formation, with the distance between the hub and each robot held constant. The deployment sequence as shown in Fig. 4 could be adopted. The wings in quadrants I and III are first deployed, followed by the wings in quadrants II and IV. All the four wings can also be simultaneously deployed, but the capability of each robot should be considered in designing the deployment strategy. Either way, the formation control issues for the four robots are the same.

To simplify the analysis for the formation control, the robots are viewed as point masses moving along the booms. Under this assumption, many techniques developed for ground robot formations can be applied. Joshi [11] developed a multilevel adaptation for multi-agent autonomous robot formation keeping. Liao et al. [12] proposed using sliding mode control for a group of nonholonomic mobile robots so that a desired formation can be achieved. Cosic [13] adopted the leader–follower approach and combined a nonlinear PI controller and an obstacle-avoiding controller for formation keeping. Rahimi et al. proposed a coherent control strategy for a multi-agent system in the presence of a time-varying formation [14]. In the case of space formation robots, it is desirable to keep the controller simple and robust. Therefore, an adaptive sliding mode controller combined with a disturbance observer is proposed in this paper to achieve the formation operation of the robots. It treats all parameter uncertainties and unmodeled dynamics as a single disturbance term. As long as the disturbance is bounded, the controller can effectively drive the robot to follow the desired trajectory. It is also capable of handling the time-varying formation or the malfunction of the robot, such as a sudden stop of one robot.

The remainder of the paper is arranged as follows. Section 2 establishes the equations of motion of the four robots operating in formation. It also provides the prototype for the controller design. In Section 3, an adaptive sliding mode controller is formulated in three steps. Numerical simulations are given in Section 4, followed by the conclusions in Section 5.

2. Dynamic model

To simplify the analysis, the four robots in Fig. 4 are viewed as mass points when developing the control strategy for formation operation. The following assumptions are also made in the formulations:

Assumption 1. The booms of the sail are regarded as rigid bodies.

Assumption 2. The dynamics of the flexible wings are not considered.

Assumption 3. For each robot, only the motion along the booms is considered.

Under the above assumptions, a schematic of the simplified system is shown in Fig. 5. The variable r_i is the distance from the geometric origin of the sail O to robot R_i. The forces exerted on each robot are classified into two parts, F_i^c and F_i^d, which are the control force and disturbing force, respectively. F_i^c originates from the torques exerted