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Autonomous assembly with collision avoidance of a fleet of flexible spacecraft based on disturbance observer

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ABSTRACT

This paper presents a distributed control law with disturbance observer for the autonomous assembly of a fleet of flexible spacecraft to construct a large flexible space structure. The fleet of flexible spacecraft is driven to the pre-assembly configuration firstly, and then to the desired assembly configuration. A distributed assembly control law with disturbance observer is proposed by treating the flexible dynamics as disturbances acting on the rigid motion of the flexible spacecraft. Theoretical analysis shows that the control law can actuate the fleet to the desired configuration. Moreover, the collision avoidance between the members is also considered in the process from initial configuration to pre-assembly configuration. Finally, a numerical example is presented to verify the feasibility of proposed mission planning and the effectiveness of control law.

1. Introduction

The structures in modern space engineering trend towards large scale and light weight, and even become too large to be launched as a whole. On-orbit autonomous assembly is a promising technique to construct such large space structures [1-3]. It usually contains two forms:(i) the modules are transported and assembled by some space robots [3-6], and (ii) each module can control its own motion to gain the desired states [7-8]. The second form is of concern in this study. The autonomous assembly and reconfiguration of several rigid spacecraft have attracted significant attention. For instance, Underwood et al. studied the optical technique and autonomous rendezvous and docking technology to fulfill the un-docking and re-docking of two nanosatellites [9]. Badawy and McInnes investigated the autonomous on-orbit assembly of a fleet of superquadric spacecraft using the potential field based method [8]. Okasha et al. developed control algorithms for the autonomous assembly of multiple spacecraft on the basis of the closed-form analytical solution of relative motion equations in a general Keplerian orbit [10].

In essential, multiple autonomous spacecraft belong to multi-agent systems, which have been widely studied over the past several decades [11-13]. However, most studies focused on the distributed control of multiple rigid spacecraft. To improve the work efficiency of assembly mission, each spacecraft is expected to be large scale and light weight. Furthermore, the modern spacecraft usually carries some large long appendages, such as solar panels, antennas, and manipulators. Hence, the member in the team should be treated as flexible spacecraft rather than rigid one. Recently, several investigators have focused on the cooperative control of multiple flexible spacecraft, which is much more challenging due to the rigid-flexible dynamics. For example, Du and Li solved the attitude synchronization for a group of flexible spacecraft without or with communication delay based on back-stepping technique [14-15]. Zou et al. presented a distributed control law for the attitude synchronization of multiple flexible spacecraft with the estimations of both modal variables and angular velocities [16]. Huang et al. designed three distributed control laws for the attitude consensus of a fleet of flexible spacecraft with actuator failures and saturation based on the Lyapunov's theory [17]. Under a leader-following architecture, Du et al. used the backstepping technique to investigate the attitude consensus of a multi-agent system, which consists of multiple rigid and flexible spacecraft [18]. Chen et al. studied the autonomous assembly of multiple planar flexible spacecraft using potential field based method and output consensus with collision avoidance of the team members [7, 19].

Over the past decades, a considerable effort has been made to the dynamics and control of single flexible spacecraft [20-25]. One effective control design method is proposed by treating the flexible dynamics as the disturbances acting on the rigid motion, i.e., the flexible spacecraft is considered as a rigid one with particular disturbances. An efficient disturbance attenuation control law is based on the disturbance observer [26-27], which can track the true unknown disturbance effectively. For example, Wang and Wu combined a nonlinear disturbance

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Nomenclature

Symbol Description

$\otimes$	Kronecker product
$\mathbf{0}$	zero matrix or zero vector
$\boldsymbol{A}$	adjacency matrix of graph
$\mathbf{B}$	$\mathrm{diag}([b_1,\ b_2,...,b_N])$, where $b_1 = 1$ and $b_i = 0$ for $i = 2,\ ...,N$.
$\mathbf{C}_{di}\dot{\mathbf{q}}_i$	structural damping force of the i-th flexible spacecraft
$\mathbf{C}_i\dot{\mathbf{q}}_i$	summation of centrifugal and the Coriolis torque/force of the i-th flexible spacecraft
D_{ij}	radial Euclidean distance between two ellipses.
	bending stiffness of beam
$\mathscr{E}$	a set of edges
$\mathbf{F}_{ca}$	collision avoidance force
$\mathbf{f}(\dot{\mathbf{x}}_i)$	nonlinear vector function of $\dot{\mathbf{x}}_i$
$\mathscr{G}$	communication graph
$\mathbf{G}_i$	$[\mathbf{I}_3\ \ 0_{3\times6}]^T$
$\mathbf{g}(\dot{\mathbf{x}}_i)$	$\frac{\mathrm{d}\mathbf{f}(\dot{\mathbf{x}}_i)}{\mathrm{d}\dot{\mathbf{x}}_i}$
$\mathbf{H}$	$\mathbf{L} + \mathbf{B}$
$\mathbf{I}_n$	$n \times n$ identity matrix
J_h	rotary inertia of rigid hub
$\mathbf{K}_i$	stiffness matrix of the i-th flexible spacecraft
$\boldsymbol{L}$	Laplacian matrix of graph
l	length of beam
$\mathbf{M}_i$	mass matrix of the i-th flexible spacecraft
m_h	mass of rigid hub
N	number of spacecraft in assembly mission
N_i	set of neighbors of the node v_i
$\mathbf{p}$	$[\mathbf{p}_1^{\mathrm{T}}\ \ ...\ \ \mathbf{p}_N^{\mathrm{T}}]^{\mathrm{T}}$
p_{Aji}	j-th modal coordinate of beam A
p_{Bji}	j-th modal coordinate of beam B
$\mathbf{p}_i$	$[p_{A1i}\ \ p_{A2i}\ \ p_{A3i}\ \ p_{B1i}\ \ p_{B2i}\ \ p_{B3i}]^{\mathrm{T}}$
$\mathbf{q}_i$	generalized coordinate vector
r	radius of rigid hub
$\mathbf{S}$	$\tanh(\boldsymbol{\beta}_1\mathbf{s})$
$\mathbf{s}$	$(\mathbf{L} \otimes \mathbf{I}_3)\bar{\mathbf{x}}$
s'	$(\mathbf{H} \otimes \mathbf{I}_3)\dot{\mathbf{x}}$
$\mathscr{V}$	a set of N nodes
V_{ca}	collision avoidance potential field
v_i	i-th node in communication graph
X_{0i}	X-coordinate of the center of the i-th hub
$\mathbf{x}$	$\mathbf{x} = [\mathbf{x}_1^{\mathrm{T}}\ \ ...\ \ \mathbf{x}_N^{\mathrm{T}}]^{\mathrm{T}}$
$\bar{\mathbf{x}}$	$\mathbf{x} - \boldsymbol{\Delta}$
$\mathbf{x}_i$	$[X_{0i}\ \ Y_{0i}\ \ \theta_i]^{\mathrm{T}}$
Y_{0i}	Y-coordinate of the center of the i-th hub
α	positive constant smaller than δ
$\boldsymbol{\Delta}$	constant offset vector defined as $[\Delta_1\ \ 0\ \ 0\ \ \Delta_2\ \ 0\ \ 0\ \ ...\ \ \Delta_N\ \ 0\ \ 0]^{\mathrm{T}}$
Δ_i	$(i-1)(2r + 2l + \delta)$ for $i = 1,\ 2,\ ...,\ N$
δ	minimum distance between adjacent spacecraft in the pre-assembly configuration
ρ	linear density of beam
$\boldsymbol{\tau}_i$	control input vector of the i-th flexible spacecraft
θ_i	attitude angle of the i-th hub

observer and feedback linearization control to solve the attitude maneuver of a flexible spacecraft [28]. Liu et al. designed a composite control law based on disturbance observer for the flexible spacecraft with model uncertainties and environment disturbances [29]. Chak et al. studied the attitude and sun-tracking control of a flexible spacecraft with the feedforward of the disturbance estimations [30]. Yan and Wu proposed a backstepping control law with an extended disturbance observer for the attitude stabilization of a flexible spacecraft with various disturbances [27]. However, all the listed literature paid attention to the control design problem of one single flexible spacecraft based on disturbance observer.

Furthermore, the requirement of collision avoidance must be considered in the assembly mission, since the members will inevitably operate in close proximity. Artificial potential field based method is widely applied to avoid inter-collision due to its analytic and continuous form. For instance, Palacios et al. presented a Riccati-based tracking control law, in which a nonlinear evasive acceleration is included based on artificial potential fields [31]. Spencer proposed an artificial potential function to drive the spacecraft to the desired relative orbits based on relative orbital elements [32].

In this study, a distributed control law with disturbance observer is presented to construct a large flexible space structure via the assembly of multiple flexible spacecraft. The collision avoidance is also taken into consideration during the mission. Compared with our previous work [7, 19], a more flexible and practical mission planning strategy is presented and the effect of the vibration of flexible appendages on the rigid motion of the flexible spacecraft is considered based on disturbance observer. Hence, the main contribution of this paper is to propose a new mission planning strategy for the construction of large slender space structure and a distributed assembly control law with disturbance observer. The rest part of the paper is organized as follows. Section 2 reviews some notations and the basic graph theory. Section 3 presents the dynamic equation of a flexible spacecraft and the designed assembly mission. An assembly control law with disturbance observer and collision avoidance is given in Section 4. In Section 5, case studies are presented to verify the assembly mission. Finally, the conclusions are drawn in Section 6.

2. Preliminaries

2.1. Notations

Assume $\mathbf{I}_n$ and $\mathbf{0}$ stand for an identity matrix of $n \times n$ and a matrix or vector with all the entries being to zero. Given matrices $\mathbf{M}_1,\ \mathbf{M}_2,\ ...,\mathbf{M}_N$ with the same dimension, the definition of $\mathrm{diag}(\mathbf{M}_1,...,\mathbf{M}_N)$ is as follows.

$$\mathrm{diag}(\mathbf{M}_1,...,\mathbf{M}_N) = \begin{bmatrix} \mathbf{M}_1 & \mathbf{0} & ... & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_2 & ... & \mathbf{0} \\ ... & ... & ... & ... \\ \mathbf{0} & \mathbf{0} & ... & \mathbf{M}_N \end{bmatrix} \tag{1}$$

The Kronecker product of matrices $\mathbf{A}_{m\times n}$ and $\mathbf{B}_{r\times s}$ is defined as

$$\mathbf{A} \otimes \mathbf{B} = \begin{bmatrix} a_{11}\mathbf{B} & ... & a_{1n}\mathbf{B} \\ ... & ... & ... \\ a_{m1}\mathbf{B} & ... & a_{mn}\mathbf{B} \end{bmatrix}_{mr\times ns} \tag{2}$$

Moreover, $\sum_{i=1}^{n}\int_{x_{i0}}^{x_i}\tanh(\beta_{1i}x_i)dx_i$ is denoted as $\int_{\mathbf{x}_0}^{\mathbf{x}}\tanh(\boldsymbol{\beta}_1\mathbf{x})d\mathbf{x}$, where $\mathbf{x} = [x_1\ \ x_2\ \ ...\ \ x_n]^{\mathrm{T}}$ and $\boldsymbol{\beta}_1 = \mathrm{diag}([\beta_{11},\ \ \beta_{12},...,\beta_{1n}])$. Consequently, the time derivative of $\int_{\mathbf{x}_0}^{\mathbf{x}}\tanh(\boldsymbol{\beta}_1\mathbf{x})d\mathbf{x}$ reads $\dot{\mathbf{x}}^{\mathrm{T}}\tanh(\boldsymbol{\beta}_1\mathbf{x})$.

2.2. Graph theory [13, 16, 18, 33]

The communication among the multi-agent system can be described by a topology graph $\mathscr{G} = (\mathscr{V},\ \mathscr{E})$, where $\mathscr{V}$ is a set of N nodes and $\mathscr{E}$ is a set of edges. The element $(v_i,\ v_j)$ of $\mathscr{E}$ represents the information flow from node v_i to v_j. The set of neighbors of the node v_i is defined as $N_i = \{v_j|(v_j,\ v_i) \in \mathscr{E}\}$, i.e., the set of the nodes from which node v_i can receive information. There are no self-loops and multiple edges between the same pairs of nodes in the graph here. If $\forall\ i,\ j,$