ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (2017) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Consensus of satellite cluster flight using an energy-matching optimal control method

Jianjun Luo [a,b], Liang Zhou [a,b,*], Bo Zhang [b,c]

[a] School of Astronautics, Northwestern Polytechnical University, Xi'an 710072, China
[b] National Key Laboratory of Aerospace Flight Dynamics, Xi'an 710072, China
[c] College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen, China

Received 20 January 2017; received in revised form 16 May 2017; accepted 7 July 2017

Abstract

This paper presents an optimal control method for consensus of satellite cluster flight under a kind of energy matching condition. Firstly, the relation between energy matching and satellite periodically bounded relative motion is analyzed, and the satellite energy matching principle is applied to configure the initial conditions. Then, period-delayed errors are adopted as state variables to establish the period-delayed errors dynamics models of a single satellite and the cluster. Next a novel satellite cluster feedback control protocol with coupling gain is designed, so that the satellite cluster periodically bounded relative motion consensus problem (period-delayed errors state consensus problem) is transformed to the stability of a set of matrices with the same low dimension. Based on the consensus region theory in the research of multi-agent system consensus issues, the coupling gain can be obtained to satisfy the requirement of consensus region and decouple the satellite cluster information topology and the feedback control gain matrix, which can be determined by Linear quadratic regulator (LQR) optimal method. This method can realize the consensus of satellite cluster period-delayed errors, leading to the consistency of semi-major axes (SMA) and the energy-matching of satellite cluster. Then satellites can emerge the global coordinative cluster behavior. Finally the feasibility and effectiveness of the present energy-matching optimal consensus for satellite cluster flight is verified through numerical simulations.

Keywords: Consensus; Energy matching; LQR; Optimal control; Period-delayed errors; Satellite cluster flight

1. Introduction

Satellite Cluster Flight (Ben-Yaacov et al., 2016; Chu et al., 2013; Mazal and Gurfil, 2014; Zhang, 2013; Zhang and Gurfil, 2015a,b; Zimmerman and Gurfil, 2015), is a form of disaggregated satellite systems configuration and operations mode. There is no requirement for precise control of relative attitude and position, but mission objectives and system requirements and constraints, including inter-satellite communications and safety aspects, dictate constraints on the cluster design and control need to be satisfied. Cluster Flight can be seen as periodically bounded relative motion.

In order to reduce the fuel consumption of the cluster system, the satellite cluster should maintain periodically bounded relative motion as long as possible, with no control force or small thrust. Satellite's orbital period depends on its orbit energy. To achieve a periodically bounded motion, they need to satisfy a kind of energy matching between satellites (energy equal or equivalent) (Gurfil, 2005; Gurfil and Mishne, 2007). Gurfil (Gurfil and Mishne, 2007) demonstrated that using only the measured

* Corresponding author at: School of Astronautics, Northwestern Polytechnical University, Xi'an 710072, China.
E-mail addresses: jjluo@nwpu.edu.cn (J. Luo), nysafeng@163.com (L. Zhou), windance86@163.com (B. Zhang).

http://dx.doi.org/10.1016/j.asr.2017.07.013
0273-1177/

Please cite this article in press as: Luo, J., et al. Consensus of satellite cluster flight using an energy-matching optimal control method. Adv. Space Res. (2017), http://dx.doi.org/10.1016/j.asr.2017.07.013

value of LOS (Lion-of-Sight) direction, which brings periodically delay state errors, exerting feedback control can realize the satellite semi-major axis convergence and energy matching. Xu studied the reference orbit dynamics and relative motion dynamics under the J2 perturbation (Xu and Wang, 2008). Morgan and Chung considering the study of Xu, found a kind of energy matched initial conditions considering the J2 perturbation and atmospheric drag perturbation, which can reduce relative drifts and fuel consumption (Morgan et al., 2012). Morgan's results had been applied for swarms of 100-Gram-Class Spacecraft space system architecture (Hadaegh et al., 2016).

In order to make satellite cluster emerge global coordination behavior and implement periodically bounded relative motion, we can analyze the problem from the perspective of consensus (Ren and Beard, 2008). In Ren's book, the problem of information consensus is addressed using distributed consensus algorithms. Recently, many scholars have conducted research on the problem of consensus. Olfati-Saber pointed out that if the topology of the multi-agent system is strongly connected digraph, then for any initial state, the states of the system asymptotically converge (Saber and Murray, 2003, 2004). Ren demonstrated that if the static time-invariant topology is given, the necessary and sufficient condition for the system to achieve consensus is an information exchange diagram contains a spanning tree (Ren et al., 2005; Ren and Beard, 2005, 2008). However, their researches mainly focus on the ground or underwater multi-agent, unmanned aerial vehicles (UAVs), etc., which are in relatively simple mechanics environment. Satellites are running in the center gravitational field with different perturbations, so that the dynamics environment makes consensus problem much more complicated. Zhang and Gurfil's work developed a distributed controller for controlling a satellite cluster to the same orbit, which inspires the study on consensus of satellite cluster (Zhang and Gurfil, 2016).

Recently, the research on optimal consensus problem has attracted attentions from many relevant scholars. The problem has not only practical application value but also profound theoretical significance. In multi-agent systems and complex network optimal consensus research, some scholars introduced the synchronization region/consensus region to analyze (Li et al., 2010; Tuna, 2008; Zhang et al., 2011). Through the establishment of a unified structure, the consensus of multi-agent systems is cast into the stability of a set of matrices of the same low dimension. It is also worth mentioning that by using the optimal design approach, the control gain design is decoupled from the communication graph structure. Finally it can realize the states of multi-agent systems to converge. Moreover, this method also has significance to the satellite cluster flight optimal consensus problem.

This paper studies the significance of the energy matching conditions for satellite cluster flight and designs a satellite cluster flight optimal control algorithm under the condition of energy matching consistency. Firstly, the relationship between energy matching and satellite periodically bounded relative motion is analyzed, and the satellite energy matching principle is referred to configure the initial conditions. Then, the period-delayed errors dynamics model of a single satellite and the cluster are established. Next based on the consensus region theory, a novel satellite cluster feedback control protocol with coupling gain is designed, so that the consensus of satellite cluster is cast into the stability of a set of matrices with the same low dimension, and the computational complexity of the problem is reduced. The coupling gain can be obtained to satisfy the requirement of consensus region in order to decouple the control gain design from the communication topology. Linear quadratic regulator (LQR) optimal method is used to determine the feedback control gain matrix. As a result, the optimal consensus protocol is finally obtained.

2. Satellite cluster flight and energy- matching

In satellite clusters, a stable periodic relative motion is required. The necessary and sufficient condition is that the period of each satellite in cluster is the same, and this condition can be referred to as a period matching condition. Assuming the reference satellite is running in the two body gravitational field, so that the orbital period T is fixed by the semi-major axis a,

$$T = 2\pi\sqrt{a^3/\mu} \tag{1}$$

where μ is the earth gravitational constant. On the other hand, in the two body gravitational field, satellite orbit semi-major axis determines the energy of unit mass,

$$E = -\mu/2a \tag{2}$$

As a result, multi-satellite cluster flight period matching condition can be transformed into energy matching condition. The condition can be expressed by the mechanical energy of any satellite S_i and S_j is equal, which can be shown as follows

$$\frac{\|\boldsymbol{V}_i\|^2}{2} + U_i = \frac{\|\boldsymbol{V}_j\|^2}{2} + U_j \tag{3}$$

where $\boldsymbol{V}_i$ and U_i denote the satellite's orbital velocity and gravity potential energy respectively.

This paper refers to the reference orbit dynamics and relative motion dynamics equations considering J2 perturbation from (Xu and Wang, 2008). The Local Vertical, Local Horizontal (LVLH) coordinate system is used to describe the satellite relative motion. The origin O is on the mass center of the relative satellite, x axis is along the radius vector; z axis pointing along the orbital angular momentum vector, and y axis completes the right-hand coordinate system, being vertical with x axis within the orbital plane. Morgan and Chung's energy matching initial conditions based on the dynamic equation mentioned above is applied to study the satellite cluster flight, which is used as the initial conditions in simulation (Morgan et al., 2012), as shown below