Acta Astronautica 75 (2012) 136–153

Contents lists available at SciVerse ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Rotational and translational integrated control for Inner-formation Gravity Measurement Satellite System ☆

Zhaohui Dang [a,*], Shengyong Tang [b], Junhua Xiang [a], Yulin Zhang [a,c]

[a] College of Aerospace and Material Engineering, National University of Defense Technology, Changsha 410073, China
[b] Research Center of Satellite Technology, Harbin Institute of Technology, Harbin 150080, China
[c] School of Aerospace, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 24 April 2011
Received in revised form
17 January 2012
Accepted 5 February 2012
Available online 28 February 2012

Keywords:
Inner-formation
Gravity measurement
Rotational dynamics
Translational dynamics
Integrated control
Control allocation

ABSTRACT

Inner-Formation Gravity Measurement Satellite System (IFGMSS) is used to explore the Earth gravity using two satellites in an inner-formation flying mode. To fulfill the mission, relative position of the two satellites is required to be zeroed and attitude of the outer satellite should be stabilized in real-time. This paper proposed an integrated control scheme for the IFGMSS, and the main idea is to use only thrusters to control the relative position and attitude. The integrated control loop contains a control law's module and a control allocation law's module. The control law based on the feedback linearization method makes nonlinear dynamics counteracted and uses PD control law to reformulate the dynamics into a linear form. The integrated control allocation law is designed to assign the commanded control force and moment to each thruster dynamically. We transfer the control allocation problem into a linear programming (LP) problem and use the Optimal Theory to calculate the corresponding thrust of each thruster. Finally, an IFGMSS mission is simulated, where the two satellites fly in a circle orbit with a 300 km's altitude. Results using the integrated control scheme and the traditional separated control scheme are compared and analyzed. It has been found that the integrated control scheme is superior to the separated control scheme in output ability, level of redundancy and fuel cost.

1. Introduction

The Inner-Formation Gravity Measurement Satellite System (IFGMSS) was proposed to measure the gravity by Zhang and Wang some years ago [1]. In IFGMSS, a proof mass located in a big satellite is used to sense the gravity [1–3]. This is done by retrieving the orbit dynamics function using the inner satellite orbit data. The IFGMSS can be regarded as a formation system, in which the proof mass is considered as a satellite, named as "inner satellite" [1]. Corresponding to the concept of 'inner satellite', the big satellite used to provide the cavity is called "outer satellite". This special formation formed by inner satellite and outer satellite is named as 'inner-formation'. This novel concept is now developing vigorously by some universities in China. IFGMSS can be seen as a new way to measure the gravity, which is different with other traditional gravity measurement satellites, like CHAMP, GRACE and GOCE [4–6]. The main feature of IFGMSS is that it constructs a virtual accelerometer by the satellite itself. In the virtual accelerometer, the inner satellite is the proof mass, and the

☆ Supported by National Natural Science Foundation of China (No. 11002076) and the Graduate Student Innovation Foundation (No. S100101) of National University of Defense Technology.

* Corresponding author. Tel.: +86 15116246544;
fax: +86 073184512301.
E-mail addresses: xydangzhaohui@yahoo.com.cn, outstandingdzh@163.com (Z. Dang), shermatang@gmail.com (S. Tang), xiangjunhua@nudt.edu.cn (J. Xiang), y.l.zhang@263.net (Y. Zhang).

0094-5765/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.actaastro.2012.02.006

outer satellite is the cavity. Therefore there are no real accelerometers to measure the non-gravitational forces in IFGMSS. Instead, it shields all the non-gravitational forces away from the inner satellite by the cavity of the outer satellite. In this sense the IFGMSS also can be seen as a drag-free system. The maintenance to this inner-formation needs a disturbance compensation system due to the non-gravitational forces such as atmosphere drag, etc. acting on the outer satellite. Or else the possible collision between inner satellite and outer satellite may occur. This can be done by controlling the outer satellite to track the inner satellite using some thrusters.

It must be remembered that the IFGMSS uses nothing other than the inner satellite as the sensor to detect the gravity signal. The cavity of the outer satellite just keeps the inner satellite away from environmental disturbances. The motion of the inner satellite may be disturbed by the outer satellite itself, too. For example, the self-gravity due to the outer satellite's mass may affect the inner satellite. This can be solved by two ways. One is to let the mass distribution of the outer satellite be away from the inner satellite as much as possible. That means the cavity size should be as great as possible. For example, the radius of the cavity in the current design has an order of tens of cms. The other way is to distribute the outer satellite mass symmetrically relative to the inner satellite. This leads to the fact that the nominal size of inner-formation in IFGMSS is zero. In other words, the center of mass (CoM) of inner satellite should be deployed at the CoM of outer satellite (coincide with the center of the cavity) as much as possible. As a result, the inner satellite freely falls in a purely gravitational orbit. Only in this condition can the orbit data of the inner satellite be used to retrieve the gravity model.

According to the above analysis, the formation maintenance in IFGMSS is crucial. To achieve this aim, there are two tasks that should be done. One is measurement of the relative state between these two satellites (inner satellite and outer satellite). The other is how to control the outer satellite tracking the inner satellite. The method to measure the relative position between these two satellites was reported by Han et al. [7]. He proposed an infrared light imaging system installed on the cavity to detect the motion of the inner satellite. Based on this scheme, Dang and Zhang [2] developed a filter algorithm to estimate the relative states (i.e. relative position, relative velocity, relative attitude and relative angular velocity) between inner satellite and outer satellite. Currently some control methods for IFGMSS have also been developed. In 2009, Dang et al. [8] designed an optimal control law to achieve the relative tracking for IFGMSS. The main feature of their method is the on-line atmosphere drag estimation, which makes it compensate for the atmosphere drag acting on the outer satellite in real-time. However, this method only considers the tracking problem of relative position without the relative attitude. In 2010, Ji et al. [9] proposed a method based on model predictive techniques to achieve the three-axis stabilization of the low earth orbiting drag-free satellite. Although it aims to solve the problem for all kinds of drag-free satellites, it mainly contributes to the IFGMSS. It was a pity that it only solved one aspect of the tracking problem in IFGMSS, namely relative attitude stabilization. In 2011, Ji et al. [10] investigated the integrated orbit and attitude control of IFGMSS during steady-state phase. A six degree-of-freedom coupled translational and rotational dynamics model with thruster layout was constructed. It was the first case in which the relative position and relative attitude are both tackled for IFGMSS. The shortage of their method was the relative dynamic model of the IFGMSS was supposed as a linear form. It may cause a great error that lowers the performance of the gravity measurement. Moreover this paper didn't give an effective control allocation method to make all the thrusters work evenly.

Enlightened by the works of Dang and Ji et al., this paper will investigate the complete control method for IFGMSS. Due to the fact that relative translational and rotational dynamics of the two satellites in IFGMSS is strongly coupled, the controller design should consider the 6 DOFs relation carefully. Due to the fact that the IFGMSS also can be seen as a drag-free satellite, the control methods that were used in traditional drag-free applications are investigated. When the proof mass is spherical, Lange [11] investigated the relative position tracking of the satellite to proof mass under on–off control. Bencze et al. [12] designed a LQG algorithm with backup PD control to keep the relative position between the proof mass and the satellite. Dohuff [13] proposed a method to control the drag-free satellite in 3 DOFs using two thrusters in a rotating mode. A method for the GOCE satellite called H-infinity technique based on a Linear Matrix Inequalities optimization procedure was proposed by Prieto [6]. An all-propulsion Embedded Model Control (EMC) was proposed by Canuto et al. [14–16], but it could be only partly implemented on the real GOCE satellite because of the immature micro-propulsion technology. However, the IFGMSS is not a traditional drag-free satellite. As a matter of fact, it relaxes the requirements of control accuracy since that the cavity size in IFGMSS is greater than other drag-free satellites. Furthermore, the inner satellite (proof mass) freely flies in the outer satellite (cavity) and it defines the corresponding reference orbit that the latter must track. The collision (between inner satellite and outer satellite) avoidance, however, should be required in IFGMSS because it will affect the gravity measurements.

The controller using only thrusters is called an all-propulsion controller [15]. Using the all-propulsion controller to control satellite in all 6 DOFs is an advanced control scheme in the future scientific and observational mission, which was proposed by E. Canuto. The adoption of the all-propulsion actuation in the IFGMSS constructs a quiet and low-vibration platform (compared with the adoption of fly wheels or gyroscopes), and provides a well condition for optical sensors to perform relative state observing. The integrated control scheme (ICS) would be compared with a separated control scheme (SCS) in this paper. The difference between these two schemes is that, SCS uses one set of thrusters to perform translational control and another set of thrusters to perform rotational control, respectively. While in ICS, all the thrusters are used to generate force and torque simultaneously.