Available online at www.sciencedirect.com
SciVerse ScienceDirect
Advances in Space Research 52 (2013) 1047–1062
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

# Optimal network topology of relative navigation and communication for navigation sharing in fractionated spacecraft cluster ☆

Zhaohui Dang *

*College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China*

Received 6 November 2012; received in revised form 6 May 2013; accepted 12 June 2013
Available online 20 June 2013

**Abstract**

Navigation sharing as a key technology provides orbit and attitude information broadcasting for the whole fractionated spacecraft cluster (FSC). The navigation sharing concept has already been proposed for some years. However, the problem of achieving the optimal navigation sharing by designing the proper network topology is still unsolved, especially in the case that some members of the cluster have absolute navigation devices, some just have relative navigation devices and some only have communication devices. In this paper, a comprehensive model of describing the navigation sharing problem in FSC is proposed. The model of network topology constructing by relative navigation links and communication links is established. By using the graph theory and genetic algorithm as the tool, the conditions for navigation sharing in FSC with different sharing degrees are obtained. Finally, some examples are presented to test the methods, and it has been found that, the absolute positions and attitudes of all the members can still be determined even some members in FSC have no absolute navigation devices.


*Keywords:* Navigation sharing; Fractionated spacecraft cluster; Relative navigation; Communication; Graph theory

## 1. Introduction

Fractionated spacecraft cluster (FSC) has become a hot topic recently, which is researched widely by lots of scientists and engineers (Jamnejad and Silva, 2008; O'Neil and Weigel, 2011; Kichkaylo et al., 2012; Dubos and Saleh, 2011; Wang and Nakasuka, 2012; Yao et al., 2012). The FSC represents a relaxed formation with multiple members which can be incomplete spacecraft assembly. Once receiving the mission command and control signal, the members in FSC can be rapidly gathered and assembled into one or more holonomic spacecrafts. Due to this characteristic, the FSC has more survivability and flexibility than the traditional spacecraft formation. To achieve the aim of distributing the FSC in space, some key technologies have been recognized, for example, the formation flight control technology, the space-based self-organized network technology, and the navigation sharing technology, etc. (Brown, 2004; Brown and Eremenko, 2006a,b). It is clear that the navigation sharing can provide the input information of the control system, which is vitally important to be studied in FSC.

The navigation sharing means that the members in a cluster exchange the navigation data with each other. In a traditional spacecraft formation, to maintain the formation configuration, the member in the formation should know its own inertial (absolute) position and attitude and others' relative position and attitude relative to it. This is done by the absolute navigation device and relative navigation device

☆ Supported by the National Natural Science Foundation of China (No. 11002076), Hunan Provincial Innovation Foundation for Postgraduate, and Graduate Student Innovation Foundation of National University of Defense Technology (No. B120101).
* Tel.: +86 13521986414; fax: +86 073184512301.
*E-mail addresses:* outstandingdzh@163.com, dangzhaohui@aliyun.com.

0273-1177/$36.00 
http://dx.doi.org/10.1016/j.asr.2013.06.009

installed in each spacecraft, respectively. By measuring one spacecraft's absolute position and attitude and relative position and attitude with respect to others, the former can obtain others' absolute navigation data, which is a simple navigation sharing in essence. This concept has also been presented in the DARPA's System F6 program (Future, Fast, Flexible, Fractionated, Free-Flying Spacecraft United by Information Exchange) (Brown and Eremenko, 2006a,b) and the personal navigation application (Isaacson, 2010). It should be noted that System F6 seeks to demonstrate the feasibility and benefits of a satellite architecture wherein the functionality of a traditional "monolithic" spacecraft is delivered by a cluster of wirelessly-interconnected modules capable of sharing their resources and utilizing resources found elsewhere in the cluster. However, in FSC, there exists the member that has no absolute navigation device. In this case, it cannot obtain either its own or others' absolute navigation data. To make up this deficiency, the communication between the deficient member and other normal ones is necessary (Dang and Zhang, 2013). In most cases, the navigation sharing assisted with communication is more efficient than the relative navigation. But it should be noted that there are some cases in which the relative navigation is necessary, for example, when no absolute navigation devices or communication devices can be used.

In our previous work (Dang and Zhang, 2013), we have discussed the concept of navigation sharing in detail. That concept is slightly different to the one stated by some other researchers (Brown and Eremenko, 2006a,b). By a comparison of the concepts given by different researchers, it has been found that our previous work limited the navigation sharing to the case of absolute navigation and communication, but Brown (2004), Brown and Eremenko (2006a,b) addressed themselves to the case in which only absolute navigation and relative navigation are considered. In fact, in real application, absolute navigation, relative navigation, and communication may all exist. In this case, how to achieve the navigation sharing is still an unsolved problem.

This paper tries to investigate the condition of the navigation sharing in FSC. For the communication device, we find two main factors which affect the navigation sharing. One is the communication channels' number which represents the number of the neighbors that one member in the cluster can communicate with. The other is the communication capacity which represents the number of the neighbors whose navigation data can be transmitted in one communication channel. For the relative navigation device, the relative navigation channels' number is the main factor which represents the number of the neighbors for which one member can perform the relative navigation. The relative navigation links and communication links among the members in FSC are modeled as the edges of directed graph, then the Graph Theory is used as the analysis tool to find the conditions for navigation sharing.

The rest of this paper is organized as follows. Section 2 gives the preliminaries and some assumptions. In this section, the concepts of navigation sharing, the definitions of some terminologies about topology graph are introduced. Section 3 presents the models and methods for navigation sharing. Three cases are discussed, then the objective function vectors are presented to optimize the network topology. The genetic algorithm for searching for the optimal network topology constructed by the relative navigation and communication links are also proposed. In Section 4, some examples are studied. The corresponding solutions are obtained and analyzed carefully. Finally, Section 5 gives some conclusions.

## 2. Preliminaries and assumptions

### 2.1. Concept and definitions

The preliminaries of navigation sharing, corresponding its definitions and related assumptions used in this paper are presented below. The definitions are used to describe the nomenclatures relative to navigation sharing. The assumptions limit the problems discussed in this paper to a rational range.

Generally, the navigation sharing means that the member in FSC exchanges the navigation data obtained by sensors or received by communication devices with others. Here 'exchange' may be real communication or virtual data transmission using relative navigation devices. Communication between two members veritably send navigation data to each other. The relative navigation can also be used to achieve this aim. This can be comprehended by the fact that the relative navigation device can determine the relative position and attitude data for the owner with respect to the target. If the owner can also determine its own absolute position and attitude, then it will obtain the wanted absolute position and attitude data of the target by adding these two kinds of data. The concept of navigation sharing is shown in Fig. 1.

The Graph Theory (Bass et al., 1974) is selected as the tool to analyze the problem of navigation sharing in this paper. To describe the network topology of relative navigation and communication links for navigation sharing, some definitions are presented as follows (Dang and Zhang, 2013):

*a. Node*

A node represents a member in FSC. It is denoted by $v_i$ where the subscript $i$ is a natural number. The total number of nodes equal to the total number of members in the cluster and denoted by $N$. Obviously, for a cluster, $N > 1$.

*b. Information*

Information or navigation information is the position and attitude data that are transmitted and received between two members. For simplicity, the information is denoted by the symbol $e_i$. Here $e_i$ represents the position and attitude of the node $v_i$. But it should be remembered that any node is not confined to only transmit its own information. A node $v_i$ can transmit information $e_j (j \neq i)$ to others as along as it has this information and others need.