Chinese Journal of Aeronautics, (2016), 29(1): 160–172

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Non-uniform hybrid strategy for architecting and modeling flight vehicle focused system-of-systems operations

Tian Yifeng, Liu Hu *, Luo Mingqiang, Huang Jun

School of Aeronautic Science and Engineering, Beihang University, Beijing 100083, China

Received 4 January 2015; revised 25 May 2015; accepted 12 October 2015
Available online 13 January 2016

KEYWORDS

Architecture;
Effectiveness;
Modeling method;
Simulation;
System-of-systems

Abstract To balance the contradiction between comprehensiveness of system-of-systems (SoS) description and cost of modeling and simulation, a non-uniform hybrid strategy (NUHYS) is proposed. NUHYS groups elements of an SoS operation into system community or relatively independent system based on contributors complexity and focus relationship according to the focus of SoS problem. Meanwhile, modeling methods are categorized based on details attention rate and dynamic attention rate, seeking for matching contributors. Taking helicopter rescue in earthquake relief as an example, the procedure of applying NUHYS and its effectiveness are verified.

1. Introduction

Since the concept of system-of-systems (SoS)[1–5] was introduced into the area of military by Owens[1] in 1996, the impact of SoS on design and application of new flight vehicle has received an increasing attention. And the influence has extended from military vehicles to airliner,[6–9] maritime applications[10] and other civilian fields. Actually, SoS has penetrated into every major phase of the vehicle life-cycle. For example, the design requirements in conceptual design phase are obviously determined according to the operations to be performed. In addition, the effectiveness of these operations should also be considered in the process of design parameter selection and design evaluation. These operations are usually complex and have the characteristics of SoS,[2] so they are called SoS operations for short in this research. Moreover, to make an optimal decision in the process of application, users, especially commanders, must take into account both performances of a flight vehicle and situation of current operation. Although crucial factors are related to a wide range of SoS operations, the attention of designers or users is basically focused on flight vehicle itself, so this type of operations can be called "flight vehicle focused SoS operations".

Modeling and simulation (M&S) has been applied as an effective way for designers and users (hereinafter generally referred to as decision-makers) to grasp the rules of SoS and then make a reasonable and optimal decision through plenty of "what-if" studies. Extensive researches on this subject have

* Corresponding author. Tel.: +86 10 82315871.
E-mail addresses: tianyifeng_buaa@163.com (Y. Tian), liuhu@buaa.edu.cn (H. Liu), luomingqiang@buaa.edu.cn (M. Luo), junh@china.com (J. Huang).

Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2016.01.002
1000-9361

been carried out, among which the typical works include a series of researches on technology assessment and stochastic SoS modeling by Georgia Institute of Technology[10,11] and the SoS design of airliner and unmanned aerial vehicle by Purdue University.[12–15] All of these works targeted at flight vehicle focused SoS operations and show some common features, such as involving the uncertainty and discontinuities, simplifying the calculation procedure by surrogate models and applying various modeling methods such as agent,[10,14] mixed integer nonlinear programming,[12] network theory,[14,15] etc.

However, the scale of most SoS operations in available literatures is relatively limited for the reason that many intricate ''stories'' behind an SoS operation are simplified. For example, the emergence of hostile time-sensitive targets may be driven by ground combat, and marine perils might be the impact of atrocious weather on a fleet. Obviously, unfolding these stories will make decision-makers get a more complete SoS operation picture and more accurate information, leading to more reasonable decisions. However, this will also increase complexity of SoS and raise the cost of M&S.

Balancing the contradiction between comprehensiveness of SoS description and cost of M&S is the major objective of this research, and two basic points provide the research idea: (1) as for flight vehicle focused SoS operations, there is no need to put equal attention on every factor involved; (2) different modeling methods differ in abstract level and computational complexity. Based on these points, a method named non-uniform hybrid strategy (NUHYS) was proposed, which provides a new approach to architect and model flight vehicle focused SoS operations through three major steps, i.e., grouping, categorizing and matching, which will be described in detail in the following sections. In order to illustrate the detailed procedure and validity of NUHYS, a helicopter rescue in the case of earthquake relief is discussed and analyzed profoundly.

2. Concept and methodology of NUHYS

2.1. System community based grouping

Architecting is the basis of modeling an SoS operation. One of the common forms of architecting SoS is a top-down or bottom-up hierarchy in aerospace related researches. For instance, de Laurentis et al.[16,17] established a taxonomy with a hierarchy which consists of α, β, γ and δ levels to guide analysis and decision; Biltgen[11] introduced an architecture that comprises SoS level, system level and subsystem level; Talley and Mavris[18] proposed a robust conceptual design method and divided SoS problem into top operational environment and scenario (OES), base level and intermediate levels.

Hierarchical architecture can help classify various problems encountered in an SoS operation into corresponding levels and clearly show the connection between each level. However, when an SoS operation is extremely complex, it is difficult to perfectly present the relationship between each factor by hierarchical architecture. Therefore, de Laurentis and Callaway[17] conducted subsystem division at every level from different aspects such as resources, operations, policy and economics, and the Department of Defense Architecture Framework (DoDAF)[19] describes SoS problem through different views. However, modeling individual units in base level, which is usually in large amount, is also an immense project.

Another significant fact is that most systems in an SoS operation do not always interact with other systems independently. In other words, some systems often behave as a group and connect with other groups or systems from the perspective of the whole group. Actually, it is a common phenomenon in human society. For instance, according to the concept of SoS, a single person could be regarded as a basic element at the base level. But it will be a difficult task to build every person as an individual model if a whole city is investigated. However, a single person usually belongs to a group, like a company, a school or a government department, and it is reasonable to use one model to describe several persons belonging to one group when a whole city is considered as an SoS. The similar properties also occur in nature, like the division of labor among leafcutter ants.[20] In this paper, the group with similar systems is defined as system community (SC).

The first step of NUHYS is grouping systems and building SC according to their similarities. For a complicated SoS, the following criteria should be met to build an SC:

(1) Independence of members of SC. Each member of an SC is an independent system that can operate on its own. Independence of systems in an SoS is an essential characteristic, so independent system is the basic unit of an SC. Although many systems could be broken down into subsystems or performance parameters, they cannot operate independently, thus they are not qualified to be defined as members of an SC.
(2) Diversity of SC scale. Due to the different group characteristics among SCs, an SC could either be a small community which contains a few systems with simple links or a large one with complicated links among many systems, or even the SC itself is an SoS which conforms to the five characteristics proposed by Maier.[2] There is one noteworthy point that one single system cannot constitute an SC.
(3) Incomplete coverage of SC. A complex SoS may contain a number of SCs, and could be covered by as many SCs as possible. However, it is unnecessary to incorporate all systems in SC due to the existence of relatively independent system (RIS). The term ''relatively'' is used in RIS because if a system is totally isolated and has no connection with others, it should be ruled out of SC or even SoS.
(4) Common interests of members of an SC. The members of an SC could interact with other SCs or systems, but the more important fact is that they share collective connections and interactions with the outside, which is also the most significant principle to determine SCs.
(5) Dynamic of SCs. The members of a complex SC are not fixed, implying that they could change over time, such as increasing in number, moving to another SC or vanishing from the SC.
(6) Non-uniqueness of SC division. Non-uniqueness results from multiple attributes of member systems. For instance, a person is an employee of Company A and also belongs to University B as an alumnus at the same time. The grouping of SC should not be affected by a specific member system, which means an SC is feasible as long as it conforms to the five rules above.

In contrast with the architecture in Ref.[21] (see Fig. 1(a)), a new architecture of SoS can be obtained through grouping (Fig. 1(b)). It is not hard to tell from the comparison that focus