Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 114 (2017) 375–383

Procedia Computer Science

www.elsevier.com/locate/procedia

Complex Adaptive Systems Conference with Theme: Engineering Cyber Physical Systems, CAS October 30 – November 1, 2017, Chicago, Illinois, USA

Coordination of Constituent Systems for Functionalizing Systems of Systems: An Exploration

Walter L. Barnes II[a], Madison Calvin[a], Katherine Linville[a], Ya-nan Song[b], Rong-hua Xu[b], Bo Zhao[c], Ruwen Qin[a]*

[a]*Department of Engineering Management and Systems Engineering, Missouri University of Science and Technology, 600 W. 14th Street, Rolla, Missouri, 65401, USA*
[b]*College of Automation, Guangdong University of Technology, Guangzhou, 510006, China*
[c]*State Grid Zhejiang Electric Power Company Research Institute, Hangzhou, Zhejiang 310014, China*

Abstract

Coordinating the constituent systems of a system of systems (SoS) in operations is an important task for functionalizing the SoS. The choice of a coordinating strategy needs to consider the autonomy, belonging, and connectivity levels of constituent systems. The diversity and emergence characteristics of SoS are outcomes of coordination. This paper analyzes different strategies for coordinating constituent systems from the perspective of SoS characteristics and, therefore, derives the mechanism for choosing a coordinating strategy. Challenges are found in implementing the coordinating strategies for SoS. The paper summarizes representative challenges facing system engineers. Methods for addressing these are proposed, including the multi-stage multi-scale coordination and smart coordination of operating mode switches. An island energy system composed of both diesel engine generators and microgrids with renewable energy sources is presented in this paper as an example of SoS network. Various aspects of coordinating constituent systems in this SoS network are presented to illustrate how the choice and execution of coordinating strategies functionalize SoS.

Peer-review under responsibility of the scientific committee of the Complex Adaptive Systems Conference with Theme: Engineering Cyber Physical Systems.

Keywords: systems of systems; constituent systems; coordination; complexity; microgrid network

* Corresponding author. Tel.: +1-573-341-4493.
E-mail address: qinr@mst.edu.

1877-0509
Peer-review under responsibility of the scientific committee of the Complex Adaptive Systems Conference with Theme: Engineering Cyber Physical Systems.
10.1016/j.procs.2017.09.051

1. Introduction

A system of systems (SoS) is an arrangement of independently managed and operated systems. A SoS has five characteristics that differentiate it from a system, which are autonomy, belonging, connectivity, diversity, and emergence [1]. Therefore, SoSs provide unique capabilities for meeting special needs for intelligence [2], [3], flexibility [4], and synergy [5], which may not be accomplished by a single system.

The five characteristics have been widely adopted as the foundation for forming, analyzing, and modeling SoS. Dimario, et al. [6] stated that the characteristics of SoS play important roles in the SoS mechanism design and social function, concluding that the SoS formation is a result of balancing multiple objectives in a satisficing environment. Similarly, Gorod, et al. [7] proposed to use both dynamic and static doctrines to manage SoS in ever changing dynamic environments, wherein the five characteristics of SoS represent the dynamic doctrine. Baldwin and Sauser [8] and Baldwin et al. [9] modeled autonomy and connectivity using set theory, and formulated belonging using game theory. Agent-based model simulation was then used to implement the model and gain better understanding of SoS formation. Preservation of the five characteristics of a SoS as it is evolving in a dynamic environment is clearly critical to functionalizing the SoS; however, not much work has been dedicated to this need.

Coordinating constituent systems of a SoS is an important task for operating SoS and so preserving the characteristics of SoS. Coordination of constituent systems must fully consider their levels of autonomy, belonging, and connectivity.

- Autonomy, to a certain degree, is currently being designed into many systems for various reasons. For example, geographically distributed systems are designed to be able to accomplish their goals without depending on the command from a central controller. Coordinating autonomous systems is not about taking charge of their functions. Instead, the coordination should respect the autonomous nature of constituent systems and still allow them to be operated and managed independently. Coordination of constituent systems takes into account the autonomous level of each individual constituent system and accordingly chooses an appropriate method to influence the management and operations of constituent systems. If the autonomous level of a constituent system can be varied, the coordination may also involve persuading constituent systems to adjust their autonomous level when needed.
- Belonging can be interpreted as choices. Systems can choose to belong or not belong. From this perspective, the coordination of constituent systems should consider their belonging level, and if possibly, identify and provide constituent systems favorable ways of SoS participation, which are likely to be accepted by constituent systems due to the benefit of choosing to belong. Likewise, the SoS chooses to allow systems to belong. From the perspective of SoS, the coordination of constituent systems involves choosing participating systems and designing their participating specifications including both requirements and compensations.
- Connections of constituent systems in a SoS are dynamic. An important aspect of coordinating constituent systems is to determine connections and disconnections of constituent systems, as well as execute the decisions. The decision and execution must take into account the connectivity of constituent systems, the anticipated benefits from connections, possible negative effects, and technical specifications of connection and disconnection.

The three characteristics discussed above are usually intertwined in coordination of constituent systems. For example, an opportunity for a system to choose to belong may require it to adjust its level of autonomy and connect with other constituent systems.

Coordination of constituent systems plays a key role in producing the diversity and emergence characteristics of SoS.

- A SoS is designed and formed to provide multiple capabilities and be capable of responding to largely uncertain conditions. Yet, the realization of diversity heavily relies on the coordination of constituent systems from perspectives of reconfiguration, dynamic assignment, and others.
- Emergence is a result of coordinating constituent systems to collaborate or cooperate. That is, the SoS is able to provide a unique function, behave in a special manner, and generate a level of utility that cannot be accomplished by a single system or a group of systems without coordination. The desired constituent system behaviors are the result of voluntary and collaborative interactions without central direction [10].

We can conclude that coordination of constituent systems is critical to preserving constituent systems' autonomy, belonging, and connectivity, and consequently generating diversity and emergence as desired SoS behaviors. However, not much formal work has been done to specify how to functionalize SoS through coordinating constituent systems. We are motivated to explore this topic and develop knowledge on it. In the remainder of the paper, we first analyze coordinating strategies in operating SoS in Section 2. Then, in Section 3, representative challenges in