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A Framework of System of Systems Design with Scenario, Multi-Agent Simulation and Robustness Assessment

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Abstract

A system of systems (SoS) is a heterogeneous, autonomous and complex systems. This paper aims at proposing a new framework of SoS design. First, this research discusses the complex situations of SoS, and addresses the three issues of SoS design: 1) nonlinearity and discontinuity of design space, 2) emergence behavior, and 3) high uncertainty. The framework adopts a scenario design method, a multi-agent simulation method, and a robust design method to solve these issues, and integrates them in a sophisticated manner. A case study of designing subsidy polices for a distributed generation system, which is a typical SoS, is demonstrated.

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Keywords: System of systems, design methodology, scenario, multi-agent simulation, robustness, distributed generation system

1. Introduction

A system of systems (SoS) is a complex system that has the complex characteristics, such as operational independence of constituent systems, managerial independence of constituent systems, geographical distribution, emergence behavior and evolutionary development processes [1]. According with the traditional systems engineering approaches, the best way to understand a complicated system is to break it down into parts recursively until the parts are so simple that can be understood and then reassemble the parts to understand the whole. The characteristics of SoS cause a situation where a change in one part of the system may have difficult-to-predict consequences in other parts, the causal relations of which cannot be explicitly modeled. System of systems engineering (SoSE) engages a more complex and holistic problem space, including organizational, managerial, policy, human/social, and political dimensions that exist in conditions of ambiguity, emergence, and uncertainty beyond the traditional systems engineering approaches [2]. However, few works address the issues of designing SoS.

This paper aims at proposing a new framework of SoS design. First, this research discusses the complex situations of SoS, and addresses the three issues of SoS design: 1) nonlinearity and discontinuity of design space, 2) emergent behavior, and 3) high uncertainty. The proposed framework adopts a scenario design method, a multi-agent simulation method, and a robust design method to solve these issues, and integrates them in a sophisticated manner. To verify the framework, a case study of designing subsidy polices for a distributed generation (DG) system in a Japanese locality [3], which is a typical SoS, is demonstrated.

2. Issues of SoS Design

Systems engineering researchers have been discussing issues of SoSE from the viewpoint of SoS characteristics. For example, Dahmann states seven challenges of SoSE, i.e., absent of a single authority, lack of structured control, emergence, difficulty of end-to-end testing, and so on [4]. This research interprets the SoS characteristics from the viewpoint of design, and focuses on the three issues.

2.1. Nonlinearity and discontinuity

Design can be seen as an exploration of solutions that meet requirements. Approaches from traditional systems engineering basically expects an approximated model of a complicated system to effectively explore a design space with differentiability and continuity.

Those approximations cannot be usually premised in SoS design problems. The complexity of SoS causes a situation where a change in one part of the system may have difficult-to-predict consequences in other parts, the causal relations of which cannot be modeled. Therefore, a behavior of SoS involves strong nonlinearity and noncontinuity, especially in the strong interaction of factors. Figure 1 illustrates an example of interactions that typically appear in SoS design problems.

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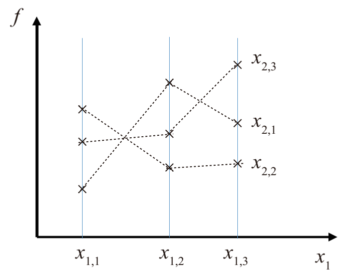

Fig. 1. Typical nonlinearity with interations

These interactions involve an objective characteristic f in terms of two variables x_1 and x_2.

2.2. Emergence behavior

Each constituent system in SoS has its own local controller with its stakeholders, users, business process and development approach. There is not a single authority responsible for the entire SoS. The SoS behavior arises only through interactions of constituent systems.

Such emergence behavior of an SoS is the source of a number of technical issues facing SoS design. The fact that a constituent system may continue to independently change the SoS, along with interdependencies between that constituent system and other constituent systems, adds to the complexity of the SoS. In particular, these dynamics can lead to unanticipated effects at the SoS level leading to unexpected or unpredictable behavior in an SoS even if the behavior of the constituent systems is well understood.

The characteristic of emergence in SoS requires to change the viewpoint of design. When a designer wants to make SoS have preferable performance, he/she should design any mechanism to give influence and incentives that lead constituent systems to behave preferably rather than control the whole system.

2.3. High uncertainty

Since design is an activity to create something new, it necessary includes uncertainty, which will make the system performance metrics unreliable. Eckert and Clarkson discussed two types of uncertainties in systems design, that is, reducible uncertainty and irreducible uncertainty [5]. The former comes from the lack of knowledge and ambiguous definition of the system. It can be reduced with additional efforts. The latter, on the other hand, can only be turned into known facts by the occurrence of future events. The way to handle this uncertainty is to manage its risk through the system operation, and give feedback to the future design.

The issues of SoS design stated above pose challenges in conducting end-to-end performance evaluation. Even when there is a clear understanding of SoS performance metrics, the degree of uncertainty is very high. The nonlinearity of a design space and the emergence behavior make it more difficult to acquire the knowledge and reduces the realm of reducible uncertainty. In addition, designing an SoS requires evaluation from a long-term viewpoint. It is very difficult to know the occurrence of future events and give feedback.

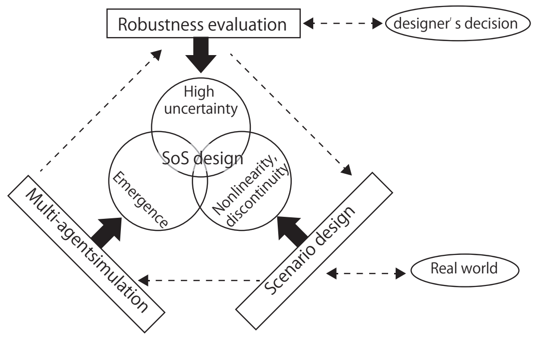

Fig. 2. SoS design framework

3. SoS Design Framework

This research proposes an SoS design framework as shown in Fig. 2. It incorporating a scenario design method, a multi-agent simulation (MAS), and a robustness evaluation method to address the issues stated in Section 2, respectively. There are many ongoing research works for addressing the issues. For example, a notion of resilience [6] is expected to a drastic solution of handling uncertainty of unpredictable conditions, while a method of " design for resilience " has not yet established. This research attempts to build a design framework with established approaches and discusses their effects and limitations toward SoS design. The details are explained in the following subsections.

3.1. Scenario design

The term "scenario" is used in many definitions [7]. One of them defines scenario as a story that connects narrative descriptions of futures with the present in a series of causal relationships. Another definition refers to consistent and coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present, and future developments, which can serve as a basis for actions. Either way, emphasis is placed on the idea that a scenario is not a prediction; rather it is an imaginative explication of possible future images that might unfold.

A scenario approach is feasible to represent alternative solutions, and to explore a design space of SoS reflecting properties of a real world. A scenario design method can facilitate to generate scenarios systematically. For example, Mizuno et al. [8] proposes a conceptual diagram of scenario design cycle consisting of three steps: (a) idea generation, (b) idea integration and scenario description, and (c) scenario evaluation.

3.2. Multi-agent simulation

MAS is a promising technique for handling emergence. MAS has evolved as extensions of other modeling techniques such as analytical and statistical modeling, cellular automata, artificial learning and others. The main contribution of MAS as a simulation technique is its ability to represent behavior of human actors, called agents, more realistically, accounting for bounded rationality, heterogeneity, interactions, evolutionary learning and out-of equilibrium dynamics, and to combine