SYSTEM OF SYSTEMS ENGINEERING

INNOVATIONS FOR THE 21st CENTURY

Edited by
MO JAMSHIDI

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THIS VOLUME IS DEDICATED JOINTLY TO:

All my mentors, in alphabetical order:

George Bekey (USC)
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who directly or indirectly taught me systems and control engineering throughout my career

Contents

Preface

In the twenty-first century, information science and technology continues to be critical benefactors of systems engineering that continue to redefine the design problem in industry, energy, defense, security, environment, and so on. Systems engineering is currently undergoing a major change to extend itself beyond a single system framework. Recently, there has been a growing interest in a class of complex systems whose constituents are themselves complex. These systems are sometimes called system of systems (SoS) or federation of systems (FoS). Performance optimization, robustness, and reliability among an emerging group of heterogeneous systems in order to realize a common goal have become the focus of various applications including military, security, aerospace, space, manufacturing, service industry, environmental systems, and disaster management, to name a few. There is an increasing interest in achieving synergy between these independent systems to achieve the desired overall system performance. Critical issues that deserve attention are coordination and interoperability in an SoS. SoS technology is believed to more effectively implement and analyze large, complex, independent, and *heterogeneous* systems working (or made to work) cooperatively. The main thrust behind the desire to view the systems as an SoS is to obtain higher capabilities and performance than would be possible with a traditional system view. The SoS concept presents a high-level viewpoint and explains the interactions between each of the independent systems. However, when it comes to engineering and engineering tools of SoS, we have a long way to go. This is the main goal of this volume. Here, we have put together 22 chapters, 8 on such fundamental issues as openness, engineering, architecture, modeling, simulation, net centricity (integration), emergence, technical evaluation, and management of SoS. In addition, a set of chapters indicative of the state of the art in current or potential applications of the technology of SoS such as defense, services, commercial airlines, transportation systems, health care, space exploration, space communication, global earth oberservation, robotics, infrastructures, electric power systems, microgrid systems, and environmental impacts are all included. Experts from all over the globe have been recruited to contribute to it. The structure of the book is as follows: Chapter 1 is a brief introduction, and Chapters 2–8 examine the fundamental issue of systems engineering as outlined from SoS point of view. Application areas are covered in Chapters 8–22.

This volume in the Wiley Series on System Engineering and Management would not have been possible without the diligent work and support of the contributing authors from industry, academia, The United States, Japan, the Netherlands, Canada, and so on. The editor thanks all of them for their contributions to SoS technology and to this volume. I wish to express my sincere appreciation and thanks to Professor Andrew P. Sage, Series Editor and an author of Chapter 3, for his encouragement to make this volume a reality. I wish to thank him, among 10 other mentors, to whom I have dedicated this volume—from my days at Oregon State University (1963–1967) to University of Illinois at Urbana-Champaign (1967–1971) to the formation of my professional career after I finished my systems and control education. Last, but by no means least, I wish to thank my dear wife, Jila Salari Jamshid, for her continuous love and support in all that I have undertaken in 34 years of companionship.

MO JAMSHIDI

San Antonio, Texas, USA
May 10, 2008

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Chapter 1

Introduction to System of Systems

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1.1 INTRODUCTION

Recently, there has been a growing interest in a class of complex systems whose constituents are themselves complex. Performance optimization, robustness, and reliability among an emerging group of heterogeneous systems in order to realize a common goal have become the focus of various applications including military, security, aerospace, space, manufacturing, service industry, environmental systems, and disaster management, to name a few (Crossley, 2004; Lopez, 2006; Wojcik and Hoffman, 2006). There is an increasing interest in achieving synergy between these independent systems to achieve the desired overall system performance (Azarnoosh et al., 2006). In the literature, researchers have addressed the issue of coordination and interoperability in a system of systems (SoS) (Abel and Sukkarieh, 2006; DiMario, 2006). SoS technology is believed to more effectively implement and analyze large, complex, independent, and *heterogeneous* systems working (or made to work) cooperatively (Abel and Sukkarieh, 2006). The main thrust behind the desire to view the systems as an SoS is to obtain higher capabilities and performance than would be possible with a traditional system view. The SoS concept presents a high-level viewpoint and explains the interactions between each of the independent systems. However, the SoS concept is still at its developing stages (Abbott, 2006; Meilich, 2006).

The next section will present some definitions out of many possible definitions of SoS. However, a practical definition may be that a system of systems is a "supersystem" comprised of other elements that themselves are independent complex

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operational systems and interact among themselves to achieve a common goal. Each element of an SoS achieves well-substantiated goals even if they are detached from the rest of the SoS. For example, a Boeing 747 airplane, as an element of an SoS, is not SoS, but an airport is an SoS, or a rover on Mars is not an SoS, but a robotic colony (or a robotic swarm) exploring the red planet, or any other place, is an SoS. As will be illustrated shortly, associated with SoS, there are numerous problems and open-ended issues that need a great deal of fundamental advances in theory and verifications. It is hoped that this volume will be a first effort toward bridging the gaps between an *idea* and a *practice*.

1.2 DEFINITIONS OF SYSTEM OF SYSTEMS

Based on the literature survey on system of systems, there are numerous definitions whose detailed discussion is beyond the space allotted to this chapter (Kotov, 1997; Luskasik, 1998; Pei, 2000; Carlock and Fenton, 2001; Sage and Cuppan, 2001; Jamshidi, 2005). Here we enumerate only six of many potential definitions:

Definition 1: Systems of systems exist when there is a presence of a majority of the following five characteristics: operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development (Jamshidi, 2005).

Definition 2: Systems of systems are large-scale concurrent and distributed systems that are comprised of complex systems (Carlock and Fenton, 2001; Jamshidi, 2005).

Definition 3: Enterprise system of systems engineering is focused on coupling traditional systems engineering activities with enterprise activities of strategic planning and investment analysis (Carlock and Fenton, 2001).

Definition 4: System of systems integration is a method to pursue development, integration, interoperability, and optimization of systems to enhance performance in future battlefield scenarios (Pei, 2000).

Definition 5: SoSE involves the integration of systems into systems of systems that ultimately contribute to evolution of the social infrastructure (Luskasik, 1998).

Definition 6: In relation to joint warfighting, system of systems is concerned with interoperability and synergism of command, control, computers, communications, and information (C4I) and intelligence, surveillance, and reconnaissance (ISR) systems (Manthorpe, 1996).

Detailed literature survey and discussions on these definitions are given in Jamshidi (2005, 2008). Various definitions of SoS have their own merits, depending on their application. Favorite definition of this author and the volume's editor is *systems of systems are large-scale integrated systems that are heterogeneous and independently operable on their own*, *but are networked together for a common goal*. The goal, as mentioned before, may be cost, performance, robustness, and so on.

1.3 CHALLENGING PROBLEMS IN SYSTEM OF SYSTEMS

In the realm of open problems in SoS, just about anywhere one touches, there is an unsolved problem and immense attention is needed by many engineers and scientists. No engineering field is more urgently needed in tackling SoS problems than system engineering (SE). On top of the list of engineering issues in SoS is the "engineering of SoS," leading to a new field of SoSE (see Chapter 3). How does one extend SE concepts such as analysis, control, estimation, design, modeling, controllability, observability, stability, filtering, simulation, and so on that can be applied to SoS? Among numerous open questions are how can one model and simulate such systems (see Chapter 5 by Mittal et al.). In almost all cases, a chapter in this volume will accommodate the topic raised.

1.3.1 Theoretical Problems

In this section, a number of urgent problems facing SoS and SoSE are discussed. The major issue here is that a merger between SoS and engineering needs to be made. In other words, SE needs to undergo a number of innovative changes to accommodate and encompass SoS.

1.3.1.1 Open Systems Approach to System of Systems Engineering Azani, in Chapter 2, discusses an open systems approach to SoSE. The author notes that SoS exists within a continuum that contains ad-hoc, short-lived, and relatively speaking simple SoS on one end, and long-lasting, continually evolving, and complex SoS on the other end of the continuum. Military operations and less sophisticated biotic systems (e.g., bacteria and ant colonies) are examples of ad-hoc, simple, and short-lived SoS, while galactic and more sophisticated biotic systems (e.g., ecosystem, human colonies) are examples of SoS at the opposite end of the SoS continuum. The engineering approaches utilized by galactic SoS are at best unknown and perhaps forever inconceivable. However, biotic SoS seem to follow, relatively speaking, less complicated engineering and development strategies allowing them to continually learn and adapt, grow and evolve, resolve emerging conflicts, and have more predictable behavior. Based on what the author already knows about biotic SoS, it is apparent that these systems employ robust reconfigurable architectures enabling them to effectively capitalize on open systems development principles and strategies such as modular design, standardized interfaces, emergence, natural selection, conservation, synergism, symbiosis, homeostasis, and self-organization. Chapter 2 provides further elaboration on open systems development strategies and principles utilized by biotic SoS, discusses their implications for engineering of man-made SoS, and introduces an integrated SoS development methodology for engineering and development of adaptable, sustainable, and interoperable SoS based on open systems principles and strategies.

1.3.1.2 Engineering of SoS Emerging needs for a comprehensive look at the applications of classical systems engineering issue in SoSE will be discussed in this volume. The thrust of the discussion will concern the reality that the technological, human, and organizational issues are each far different when considering a system of systems or federation of systems and that these needs are very significant when considering system of systems engineering and management.

As we have noted, today there is much interest in the engineering of systems that are comprised of other component systems, and where each of the component systems serves organizational and human purposes. These systems have several principal characteristics that make the system family designation appropriate: operational independence of the individual systems; managerial independence of the systems; often large geographic and temporal distribution of the individual systems; emergent behavior, in which the system family performs functions and carries out purposes that do not reside uniquely in any of the constituent systems but which evolve over time in an adaptive manner and where these behaviors arise as a consequence of the formation of the entire system family and are not the behavior of any constituent system. The principal purposes supporting engineering of these individual systems and the composite system family are fulfilled by these emergent behaviors. Thus, a system of systems is never fully formed or complete. Development of these systems is evolutionary and adaptive over time, and structures, functions, and purposes are added, removed, and modified as experience of the community with the individual systems and the composite system grows and evolves. The systems engineering and management of these systems families pose special challenges. This is especially the case with respect to the federated systems management principles that must be utilized to deal successfully with the multiple contractors and interests involved in these efforts. Please refer to the paper by Sage and Biemer (2007) and DeLaurentis et al. (2007) for the creation of a SoS Consortium (i.e., International Consortium on System of Systems (ICSoS)) of concerned individuals and organizations by the author of this chapter. Chapter 3 by Wells and Sage discusses the challenges of engineering of SoS.

1.3.1.3 Standards of SoS System of systems literature, definitions, and perspectives are marked with great variability in the engineering community. Viewed as an extension of systems engineering to a means of describing and managing social networks and organizations, the variations of perspectives lead to difficulty in advancing and understanding the discipline. Standards have been used to facilitate a common understanding and approach to align disparities of perspectives to drive a uniform agreement to definitions and approaches. By having the ICSoS (DeLaurentis et al., 2007) represent to the IEEE and INCoSE for support of technical committees to derive standards for system of systems will help unify and advance the discipline for engineering, healthcare, banking, space exploration, and all other disciplines that require interoperability among disparate systems.

1.3.1.4 System of Systems Architecting Dagli and Kilicay-Ergin in Chapter 4 provide a framework for SoS architectures. As the world is moving toward a networked society, the authors assert the business and government applications require integrated systems that exhibit intelligent behavior. The dynamically changing environmental and operational conditions necessitate a need for system architectures that will be effective for the duration of the mission but evolve to new system architectures as the mission changes. This new challenging demand has led to a new operational style: instead of designing or subcontracting systems from scratch, business or government gets the best systems the industry develops and focuses on becoming the lead system integrator to provide SoS. SoS is a set of interdependent systems that are related or connected to provide a common mission. In the SoS environment, architectural constraints imposed by existing systems have a major effect on the system capabilities, requirements, and behavior. This fact is important, as it complicates the systems architecting activities. Hence, architecture becomes a dominating but confusing concept in capability development. There is a need to push system architecting research to meet the challenges imposed by new demands of the SoS environment. This chapter focuses on system of systems architecting in terms of creating meta-architectures from collections of different systems. Several examples are provided to clarify system of systems architecting concept. Since the technology base, organizational needs, and human needs are changing, the system of systems architecting becomes an evolutionary process. Components and functions are added, removed, and modified as owners of the SoS experience and use the system. Therefore, in Chapter 4 evolutionary system architecting is described and the challenges are identified for this process. Finally, the authors discuss the possible use of artificial life tools for the design and architecting of SoS. Artificial life tools such as swarm intelligence, evolutionary computation, and multiagent systems have been successfully used for the analysis of complex adaptive systems. The potential use of these tools for SoS analysis and architecting is discussed, by the authors, using several domain application specific examples.

1.3.1.5 SoS Simulation Sahin et al. (2007) have presented an SoS architecture based on Extensible Markup Language (XML) in order to wrap data coming from different systems in a common way. The XML can be used to describe each component of the SoS and their data in a unifying way. If XML-based data architecture is used in an SoS, the only requirement for the SoS components is to understand/parse XML file received from the components of the SoS. In XML, data can be represented in addition to the properties of the data such as source name, data type, importance of the data, and so on. Thus, it does not only represent data but also gives useful information that can be used in the SoS to take better actions and to understand the situation better. The XML language has a hierarchical structure where an environment can be described with a standard and without a huge overhead. Each entity can be defined by the user in the XML in terms of its visualization and functionality. As a case study in this effort (see Chapter 5 by Mittal et al.), a master-scout rover combination represents an SoS where for the first time a sensor detects a fire in a field. The fire is detected by the master rover and commands the scout rover to verify the existence of the fire. It is important to note that such an architecture and simulation do not need any mathematical model for members of the systems.

1.3.1.6 SoS Integration Integration is probably the key viability of any SoS. Integration of SoS implies that each system can communicate and interact (control) with the SoS regardless of their hardware, software characteristics, or nature. This means that they need to have the ability to communicate with the SoS or a part of the SoS without compatibility issues such as operating systems, communication hardware, and so on. For this purpose, an SoS needs a common language the SoS's systems can speak. Without having a common language, the systems of any SoS cannot be fully functional and the SoS cannot be adaptive in the sense that new components cannot be integrated to it without major effort. Integration also implies the control aspects of the SoS because systems need to understand each other in order to take commands or signals from other SoS systems. See Chapter 6 by Cloutier et al. on network centric architecture of SoS.

1.3.1.7 Emergence in SoS Emergent behavior of an SoS resembles the slowdown of the traffic going through a tunnel, even in the absence of any lights, obstacles, or accident. A tunnel, automobiles, and the highway, as systems of an SoS, have an emergent behavior or property in slowing down (Morley, 2006). Fisher (2006) has noted that an SoS cannot achieve its goals depends on its emergent behaviors. The author *explores* "interdependencies among systems, emergence, and interoperation" and develops maxim-like findings such as these: (1) Because they cannot control one another, autonomous entities can achieve goals that are not local to themselves only by increasing their influence through cooperative interactions with others. (2) Emergent composition is often poorly understood and sometimes misunderstood because it has few analogies in traditional systems engineering. (3) Even in the absence of accidents, tight coupling can ensure that a system of systems is unable to satisfy its objectives. (4) If it is to remain scalable and affordable no matter how large it may become, a system's cost per constituent must grow less linearly with its size. (5) Delay is a critical aspect of systems of systems. Chapter 7 by Keating will provide a detailed perspective into emergence property of SoS.

1.3.1.8 SoS Management: The Governance of Paradox Sauser and Boardman, in Chapter 8, present an SoS approach to the management problem. They note that the study of SoS has moved many to support their understanding of these systems through the groundbreaking science of networks. The understanding of networks and how to manage them may give one the fingerprint that is independent of the specific systems that exemplify this complexity. The authors point out that it does not matter whether they are studying the synchronized flashing of fireflies, space stations, structure of the human brain, the internet, the flocking of birds, a future combat system, or the behavior of red harvester ants. The same emergent principles apply: large is really small, weak is really strong, significance is really obscure, little means a lot, simple is really complex, and complexity hides simplicity. The conceptual foundation of complexity is paradox, which leads us to a paradigm shift in the SE body of knowledge.

Paradox exists for a reason and there are reasons for systems engineers to appreciate paradox even though they may be unable to resolve them as they would a problem specification into a system solution. Hitherto paradoxes have confronted current logic only to yield at a later date to more refined thinking. The existence of paradox is always the inspirational source for seeking new wisdom, attempting new thought patterns, and ultimately building systems for the "flat world." It is our ability to govern, not control, these paradoxes that will bring new knowledge to our understanding on how to manage the emerging complex systems called system of systems.

Chapter 8 establishes a foundation in what has been learnt about how one practices project management, establishes some key concepts and challenges that make the management of SoS different from our fundamental practices, presents an intellectual model for how they classify and manage an SoS, appraises this model with recognized SoS, and concludes with grand challenges for how they may move their understanding of SoS management beyond the foundation.

In the previous section, a brief introduction was presented for six theoretical issues of SoS, that is, integration, engineering, standards, open and other architectures, modeling, infrastructure, and simulation. These topics are discussed in great detail by a number of experts in the field in chapters in the book.

1.3.2 Implementation Problems

Besides from many theoretical and essential difficulties with SoS, there are many implementation challenges facing SoS. Here, some of these implementation problems are briefly discussed and references are made to some with their full coverage.

1.3.2.1 Systems Engineering for the Department of Defense System of Systems

Dahmann and Baldwin, in Chapter 9, have addressed the national defense aspects of SoS. Military operations are the synchronized efforts of people and systems toward a common objective. In this way from an operational perspective, defense is essentially a "system of systems" enterprise. However, despite the fact that today almost every military system is operated as part of a system of systems, most of these systems were designed and developed without the benefit of systems engineering at the SoS level factoring the role the system will play in the broader system of systems context. With changes in operations and technology, the need for systems that work effectively together is increasingly visible. Chapter 9 outlines the changing situation in the defense department and the challenges it poses for systems engineering.

1.3.2.2 e-Enabling and SoS Aircraft Design Via SoSE

A case of aeronautical application of SoS worth noting is that of e-enabling in aircraft design as a system of an SoS at Boeing Commercial Aircraft Division (Wilber, 2007). The project focused on developing a strategy and technical architecture to facilitate making the airplane (Boeing 787, see Fig. 1.1) network-aware and capable of leveraging computing and network advances in industry. The project grew to include many ground-based architectural components at the airlines and at the Boeing factory, as well as other key locations such as the airports, suppliers, and terrestrial Internet Service Suppliers (ISPs).

Wilber (2007) points out that the e-enabled project took on the task of defining a system of systems engineering solution to problem of interoperation and communication with the existing, numerous, and diverse elements that make up the airlines'

FIGURE 1.1 A photo of the new SoS e-enabled Boeing 787 (courtesy of Boeing Company, see also Chapter 10 by G.R. Wilber)

operational systems (flight operations and maintenance operations). The objective has been to find ways of leveraging network-centric operations, to reduce production, operations and maintenance costs for both Boeing and the airline customers.

> One of the key products of this effort is the "e-enabled architecture." The e-enabling architecture is defined at multiple levels of abstraction. There is a single top-level or "reference architecture" that is necessarily abstract and multiple "implementation architectures." The implementation architectures map directly to airplane and airline implementations and provide a family of physical solutions that all exhibit common attributes and are designed to work together and allow re-use of systems components. The implementation architectures allow for effective forward and retrofit installations addressing a wide range of market needs for narrow and wide-body aircraft.
>
> The 787 "Open Data Network" is a key element of one implementation of this architecture. It enabled on-board and off-board elements to be networked in a fashion that is efficient, flexible, and secure. The fullest implementations are best depicted in Boeing's GoldCare Architecture and design.

Wilber, in Chapter 10, presents an architecture at the reference level and how it has been mapped into the 787 airplane implementation. *GoldCare* environment is described and is used as an example of the full potential of the current e-enabling.

1.3.2.3 A System of Systems Perspective on Infrastructures Thissen and Herder, in Chapter 11, touch upon a very important application in the service industry (see also Chapter 13 by Tien). Infrastructure systems (or infrasystems) providing services such as energy, transport, communications, and clean and safe water are vital to the functioning of modern society. Key societal challenges with respect to our present and future infrastructure systems relate to, among other things, safety and reliability, affordability, and transitions to sustainability. Infrasystem complexity