Identifying Top Challenges for International Research on Requirements Engineering for Systems of Systems Engineering

Cornelius Ncube, Soo Ling Lim, and Huseyin Dogan
Software Systems Research Centre
Bournemouth University, UK
{cncube; slim; hdogan}@bournemouth.ac.uk

***Abstract*—Due to an increasingly connected society and industry, our modern societal world and all industry sectors now increasingly depend on large-scale complex Systems of Systems (SoS). The emerging interdisciplinary area of SoS and Systems of Systems Engineering (SoSE) is largely driven by societal needs including public services such as health, transport, water, energy, food security, etc. The scale, complexities and challenges presented by SoS require us to go beyond traditional Requirements Engineering (RE) approaches. However, as is evident from publications in major Requirements Engineering conferences and journals, no significant effort has been expedited towards addressing specific RE issues for Systems of Systems Engineering. This panel explores key RE challenges in Systems of Systems Engineering, specifically, the areas in which the international RE community need to focus its research, and the approaches that are most likely to meet these challenges effectively. We first introduce Systems of Systems Engineering and outline key characteristics of SoS. We conclude by arguing that there is an urgent need for the global RE community to develop new ways of thinking, new capabilities and possibly a new science as a key mechanism for addressing requirements complexities posed by Systems of Systems.**

***Index Items*—Systems of Systems, Systems of Systems Engineering, Requirements Engineering, Complexity, Panel Discussion, Research Agenda and Roadmap**

I. INTRODUCTION

Many societal challenges of the 21st Century, such as global climate change, health, social care, food security, planning the future resources of the planet, sustainable transport, energy resources, and integrated economy are global in nature [1]. Consequently they are beyond the capacity of any one discipline, sector, country, or region to handle or one aspect of policy to address. The emerging area of Systems of Systems Engineering (SoSE) presents a potential for solving many of these challenges [2]. Unlike traditional Systems Engineering which focuses on building the right system, Systems of Systems Engineering focuses on selecting the right combination of constituent systems and their interactions to satisfy a set of frequently changing goals and requirements. Thus, SoSE requires a different set of skills and, to a significant extent, involves more stakeholders than traditional systems engineering. In a SoS there are stakeholders at the SoS level and at the constituent system level. These stakeholder groups each have their own objectives with respect to the SoS [3]. SoS stakeholders may have limited knowledge of the constraints and development plans of each constituent system. Similarly, stakeholders of individual constituent systems may have little interest in the SoS, may give SoS needs low priority or may resist SoS demands on their systems. These competing stakeholder interests establish a complex stakeholder environment which current requirements engineering approaches cannot adequately address [3]. Also in a single system, operational objectives are established based on structured requirements along with defined concepts of operation [4]. A SoS is engineered to create operational capabilities that are beyond that which the constituent systems can provide independently. Requirements are defined as either Systems of Systems requirements which are properties of the overall system-of-systems or constituent system-level requirements which are allocated to particular constituent system(s). The requirements for the SoS are defined in terms of capabilities rather than atomic requirements as is in the traditional systems engineering.

The main goal of this panel is to identify key Requirements Engineering challenges in Systems of Systems Engineering in which the international RE community should focus its research. We aim to use these key challenges to define a shared international RE vision and to establish a research roadmap that will address the development of techniques, processes, methods and technologies for Requirements Engineering for Systems of Systems

II. SYSTEMS OF SYSTEMS ENGINEERING AND SYSTEMS OF SYSTEMS

SoSE aims to overcome the inadequacy of traditional Systems Engineering approaches by looking beyond isolated systems to see the integrated SoS [5]. Thus SoSE requires a different mind-set, different set of skills, different techniques, tools, methods and processes than currently used in requirements engineering approaches.

Characteristics and Types of Systems of Systems

There are significant differences between monolithic complex systems (e.g. an Aircraft) and Systems of Systems (e.g. an Airport). An Airport is an example of a SoS, as it combines aircrafts baggage-handling, traffic control

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management, check-in, retail, maintenance, customs, border control and passenger care systems to ensure that passengers can get from one destination to another [6].

Therefore Systems of Systems are distinguished from very large but monolithic complex systems by (a) the *operational independence* of their constituent systems, i.e.; each constituent system can operate independently and is capable of achieving its own goals in the absence of the other systems; (b) *managerial independence* of their constituent systems, i.e.; the constituent systems are managed independently and can be added or removed from the System of Systems; (c) their *evolutionary nature* in which functions and purposes are added, removed or modified as needed, i.e.; the SoS adapts to fulfil its (possibly evolving) objectives as its underlying technologies and needs evolve with time; (d) their *emergent behaviours* that cannot be localised to any constituent system, i.e.; the functionality and behaviour of the SoS develops in ways not achieved by the individual systems, and (e) a *geographical distribution* that limits the interaction of the constituent systems to information exchange [2].

Systems of Systems are further categorised [5] as either:

- *directed,* in which the interoperable System of Systems is built and managed to fulfil specific purposes. The constituent systems are contractually subordinated to a central management of the SoS. The U.S. Army Future Combat System is an example of a directed SoS.
- *acknowledged,* in which there are recognised objectives, a designated manager and resources for the SoS. However, the constituent systems return their independent ownership, objectives, funding, development and sustainment approaches. The Ballistic Missile Defence System is an example of an acknowledged SoS.
- *collaborative*, in which constituent systems 'voluntarily' collaborate in an agnostic way to achieve an agreed-upon central purpose. The central players collectively decide how to provide or deny service, thereby providing some means of enforcing and maintaining standards. The global financial system is an example of a collaborative SoS.
- *virtual*, in which there is no central management authority and centrally agreed purpose for the SoS. Large-scale behaviour emerges and this type of SoS relies on relatively invisible mechanisms to maintain it. The Global Information Grid is an example of a virtual SoS.

Identifying the type of a SoS at the conception stage is key as it influences the entire requirements engineering approach. Dahmann and Baldwin [5] proposed a simple process for determining the type of a SoS. MacDiarmid et al. [7] proposed a taxonomy for a requirements engineering approach once the type of a SoS has been determined.

TABLE I. TAXONOMY FOR AN RE APPROACH. ADAPTED FROM MACDIARMID ET AL.[7]

SoS Type	***RE Approach***
Directed	- Classical RE methods; - Each SoS element clearly defined by central RE authority; - SoS RE evolution controlled and coordinated by central authority; - Central allocation of requirements.
Acknowledged	- RE performed by SoS central authority; - RE also performed independently by SoS elements; - Infrequent collaboration of RE artefacts.
Collaborative	- RE performed by SoS elements; - Central authority limited to expression of global SoS goals; - High levels of RE collaboration.
Virtual	- No central authority RE input; - SoS element RE informal and irregular, if at all.

III. SOME KEY REQUIREMENTS ENGINEERING CHALLENGES OF SYSTEMS OF SYSTEMS

The prevailing assumptions of the current RE approaches is that everything flows from the requirements. This logic requires that a good model of the system with fixed requirements exists; that the system problem is well bounded, the environment is relatively stable and that there is sufficient knowledge and understanding to define systems attributes and interactions [3][4]. However, the scale and complexity of SoS makes it "impossible to acquire all the knowledge and maintain a complete understanding of the system" in a single frame of vision in the face of constantly evolving and changing systems goals and requirements [8]. Also, traditional approaches successively decompose a system "top down from user requirements through to system solution components" [4]. However, in Systems of Systems Engineering the reductionist approaches that require that "a problem be properly defined, the system boundaries established and fixed cannot be supported" [4].

The emergence of Systems of Systems Engineering presents a significant departure from single-system-centric approaches and therefore a paradigm shift is required to fundamentally re-think current practices [8]. Traditional requirements engineering practices and approaches therefore need to evolve as new RE processes, techniques, methods and tools will be required to cope with challenges posed by Systems of Systems.

IV. MIXED CRITICALITY SYSTEMS WITH BLURRED BOUNDARIES

An added challenge to RE for SoS is defining the boundary of a SoS as it changes over time. Many large-scale systems of societal significance rely on integrated SoS, shared enterprises, national or worldwide critical infrastructures. It is more likely that both critical and non-critical systems will share infrastructures thus blurring the boundaries between societies, industries and economies. As such, many of these systems are likely to be mixed criticality systems that require high availability or have safety and/or security implications [9][10]. As critical and non-critical Systems of Systems cross boundaries and share infrastructures, mixed criticality systems requirements will become a major challenge. Policy makers and regulators will have to 'mediate the blurring lines between sectors, industries and systems' [1]. Requirements Engineers will need to work with regulators and policymakers as they will play a vital role when defining mixed criticality requirements. As SoS boundaries are dynamic, this poses significant challenges to manage risks associated with multiple interactions across infrastructures, domains, policies and regulations.

V. IDENTIFYING TOP REQUIREMENTS ENGINEERING CHALLENGES

As is evident from publications in major Requirements Engineering conferences and journals over the last couple of years, no significant effort has been expedited towards addressing specific requirements engineering issues for Systems of Systems Engineering. In this panel, four distinguished Requirements Engineering and Systems of Systems Engineering experts have been invited to share their ideas in identifying key SoSE areas of research that the RE community need to focus on immediately.

The panel session will include a brief presentation by each panel member. *Dr Judith Dahmann* will discuss 'SoS Requirements Space' versus 'Requirements' i.e.; in a SoS, requirements are taken on by the systems to meet the SoS objectives as part of identifying requirements and solutions options. *Professor Nancy Mead* will discuss challenges of security and trustworthiness in SoS, i.e.; that the problem of composing systems, while demonstrating security across the resultant system of systems is very difficult. *Mr Alan Harding* will focus on 'change' i.e.; changes to the purpose of the SOS, its external context, or the availability and configuration of the constituent systems within the SoS. *Professor Anthony Finkelstein* will discuss requirements engineering for large-scale complex software intensive systems

The open discussion will address the questions: "*What are the top five Requirements Engineering challenges in SoSE in which the requirements engineering community should focus its efforts on?*" and *"What methods, tools, techniques are likely to meet these challenges most effectively?"*

The intention of this panel is to identify key requirements engineering challenges for Systems of Systems Engineering and to define a roadmap for use by the international Requirements Engineering community in planning their research programmes to address these challenges.

Our hope is that this panel will provide a basis for encouraging international co-operation and collaboration in RE for SoSE research and education. We hope that this panel will strengthen and foster collaborations between the Systems Engineering, Systems of Systems Engineering and Requirements Engineering communities. Finally, we hope that this panel will provide input to establishing the embryonic RE for SoSE as a 'living forum' for sharing ideas; help establish a community of interest and influence the programmes of future Requirements Engineering conferences.

VI. PANEL MEMBERS

This panel will be moderated by **Dr Cornelius Ncube** who is the Director of the Software Systems Research Centre and the founding Director of the Systems Engineering and Information Assurance (SEnIA) Initiative at Bournemouth University, UK. Cornelius' current research interest is in Requirements Engineering for Systems of Systems.

Panelists include **Dr Judith Dahmann** who is a Principal Senior Scientist at the MITRE Corporation Center for Advanced Systems Analysis and Acquisition. Dr Dahmann is currently a Technical Advisor to the Director of Defense Systems and Systems Engineering in the U.S. DoD Under Secretary of Defense for Acquisition, Technology and Logistics; **Professor Nancy R. Mead** who is a Principal Researcher in the CERT Program at the Software Engineering Institute (SEI) with expertise in security requirements engineering and the development of software assurance curricula; **Alan Harding** who is the President of INCOSE UK, and Chair of the BAE Systems global community of practice in Systems Engineering with the responsibility of shaping BAE Systems' global engineering processes and **Professor Anthony Finkelstein** who is a Professor of Software Systems Engineering and Dean of the Faculty of Engineering Science at University College London (UCL), UK, with research interests in requirements engineering and the development of large and complex software intensive systems.

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