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IEEE-Reliability Society. Technical Committee on ' Systems of Systems'- WHITE PAPER

1. Introduction: what is a system of systems?

Over the last decade or so, the concept of " System of Systems" (SoS) has emerged. While the concept of "System" has more universal acceptance, the definition of "System of Systems" depends on the application areas and their focus.

A system is a group of interacting elements (or subsystems) having an internal structure which links them into a unified whole. The boundary of a system is to be defined, as well as the nature of the internal structure linking its elements (physical, logical, etc.). Its essential properties are autonomy, coherence, permanence, and organization [Dupuy, 1985; Kröger and Zio, 2011].

A complex system [Guckenheimer and Ottino, 2008] is made by many components interacting in a network structure. Most often, the components are physically and functionally heterogeneous, and organized in a hierarchy of subsystems that contributes to the system function. This leads both to structural and dynamic complexity [Zio, 2014]. Structural complexity derives from i) heterogeneity of components across different technological domains due to increased integration among systems and ii) scale and dimensionality of connectivity through a large number of components (nodes) highly interconnected by dependences and interdependences. Dynamic complexity manifests through the emergence of (unexpected) system behavior in response to changes in the environmental and operational conditions of its components. An often-quoted example of emergent behavior is that of a school of fish: without there being a 'master fish' that leads the school, the latter seems to acquire an 'intelligent' behavior that transcends that of every individual fish. Emergent behavior is sometimes positive (as in the case of the school of fish) but sometimes undesirable, i.e. it can lead to unintended consequences. In addition, uncertainty is considered "pervasive in complex systems" and its quantification and propagation is a "key aspect in reliable prediction and control" [Guckenheimer and Ottino, 2008].

With respect to systems of systems, no standard definition exists as yet. Boardman et al. collected around 40 definitions taken from academic literature, conference proceedings/presentations, and documentation that have been independently published by industry, government and academia [Boardman et al., 2006].

One definition (Popper 2004) is 'a collection of task-oriented or dedicated systems that pool their resources and capabilities together to obtain a new, more complex 'meta-system' which offers more functionality and performance than simply the sum of the constituent systems".

Kotov defines them using the expression "complex systems". [Kotov, 1997] states that "systems of systems are large scale concurrent and distributed systems that are comprised of complex systems".

Another interpretation of the concept of system of systems is given by Maier that identifies five properties (also known as "Maier's criteria") [Maier, 1996; Maier, 1998]: i) operational independence, i.e., each system is independent and it achieves its purposes by itself, ii) managerial independence, i.e., each system is managed in large part for its own purposes rather than the purposes of the systems of systems, iii) geographic distribution, i.e., a system of systems is distributed over a large geographic extent, iv) emergent behavior, i.e., a system of systems has capabilities and properties that do not reside in the component systems, and v) evolutionary development, i.e., a system of systems evolves with time and experience. The last three properties (iii – v) are the same as those that characterize a complex system, thus, it can be drawn that, according to Maier's definition, the difference between a complex system and a system of systems is determined by the first two properties (i and ii).

Based on Maier's criteria, Sage and Cuppan specify that systems of systems exist when there is a presence of a majority of the mentioned five characteristics [Sage and Cuppan, 2001]. Then, the following definition by De Laurentis [2007] encapsulates Maier's criteria and captures additional aspects, such as heterogeneity of component systems and multi-level structure: "A system of systems consists of multiple, heterogeneous, operationally, distributed, occasionally independently, operating systems embedded in networks at multiple levels that evolve over time" [De Laurentis, 2007].

An example of system of systems is the US National Airspace System (NAS), which involves several transportation systems that are operated independently but have to share the same space and somehow cooperate.Other examples of systems of systems include [Jamshidi, 2009]: service industry (e.g., infrastructure systems), electric power grids (large-scale, complex, dynamical systems that must operate reliable to supply electrical energy to customers, in addition they are affected by the increasing utilization of renewable energy resources), transportation systems (a system-of-systems approach is needed for a more complete model and understanding of the national transportation system [De Laurentis, 2009]), healthcare systems [Wickramasinghe et al., 2009], national defense (military systems were designed and developed individually, but nowadays the changes of operations and technologies call for the need of systems that work together [Dahmann, 2009]), aeronautical field, (e.g., e-enabling in aircraft design as a system of SoS at Boeing Commercial Aircraft Division [Wilber, 2009]), sensor networks (multiple sensing devices that work cooperatively and collaboratively [Sridhar et al., 2009]), space explorations (that deal with extremely large, complex, and intertwined command and control and data distribution ground networks [Jolly and Muirhead, 2009]), communication and navigation networks for the space (that require system interoperability, enhanced reliability, common interfaces, dynamic operations, and autonomy in system management [Bhasin and Hayden, 2009]), sustainable environmental management (e.g., solutions to global warming problems [Hipel et al., 2009]), robotic swarms [Sahin, 2009], Global Earth Observation Systems of Systems (GEOSS – a global project with more than 60 nations involved to improve the coordination of strategies and systems for Earth observations [Shibasaki and Pearlman, 2009]), and others.

In synthesis, typical characteristics of Systems of Systems include (Maier 1998, De Laurentis 2005):

- Operational and managerial independence
- Geographical distribution
- Emergent behavior
- Evolutionary development
- Heterogeneity of constituent systems

A key aspect of systems of systems is *interconnection between otherwise independent systems.*

Related relevant concepts include, for instance:

- Dependent and cascading failures
- Copulas (non-linear correlations)
- Self-organizing properties (including criticality)
- Complex event processing
- Chaotic behavior
- Scale-free phenomena
- Weak coupling
- Weak signals

The above system-of-systems traits make it difficult to build and manage it with traditional engineering practices. According to [Fisher, 2006], monolithic systems depend on central control, global visibility, hierarchical structures, and coordinated activities, but these characteristics cannot be expected in systems of systems that are related to distributed control, cooperation, influence, cascade effects, emergent behaviors [Béjar et al., 2009]. To deal with these issues, new approaches have to be identified.

In fact, it is expected that those new approach will shed more light on “traditional” systems as well.

2. Implications for Reliability and, more generally, Dependability

- Today, in many reliability and availability analyses stochastic independence is still assumed (e.g., in analyses by reliability-block diagrams, fault trees, etc.), and ‘lack of memory’ in the stochastic processes of component state transition is also assumed (markovian systems)
- Yet, dependent and cascading failures are key aspects to be accounted for in system reliability, availability and safety analyses
- IEC 61508 Appendix 6 gives some ‘recipes’ (beta factor) for modeling common cause failures. This is a good beginning but still somewhat a ‘cookbook’, rule-of-thumb’ approach. More sophisticated and elaborated approaches have been developed in the nuclear power field.
- No method apparently exists for modeling emerging behavior, within reliability, availability and safety analyses.
- Some attempts at modeling ‘weak interactions’ (e.g. by stochastic Petri nets, agent-based modeling etc.) are found in the literature and begin to make their way, albeit slowly, in industrial applications.

3. Goals of the IEEE-RS Technical Committee on Systems of Systems

In view of the above, the IEEE Reliability Society has decided to set up a technical committee (TC) on systems of systems, with the following general goals (to be refined and evolved).

1) To assess the importance of systems of systems for reliability, and more generally dependability (RAMS: reliability, availability, maintainability and safety) practitioners and theoreticians.
2) To contribute to the development and clarification of the related concepts, for their implication in dependability/RAMS engineering.
3) To increase the awareness and competence on the subject among the IEEE-RS members and the reliability community at large.
4) To foster the development of relevant methodologies and tools, with their critical assessment.

4. Proposed next steps

1) A worldwide survey of IEEE-RS chapters needs and activities in the area (ongoing)
2) An "off-program" session will be organized during RAMS 2015 (end January 2015) in Florida, to stimulate discussion and confrontation on the subject.
3) The TC will be the IEEE-RS arm in the technical program committee of the next " Systems of Systems Engineering" conference to be held in May 2015 in San Antonio, TX. Such conference is co-sponsored by IEEE Systems, Man & Cybernetics and IEEE-RS.
4) The February 2016 issue of IEEE-RS 'Reliability Digest' will be devoted to Systems of Systems.
5) To be confirmed : an "on-program" session could be organized for RAMS 2016.

More actions may be defined as a result of 1) and 2).

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