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Taxonomy of Systems-of-Systems

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Abstract

The study of systems-of-systems is an increasingly important topic in systems engineering. Though there is not complete agreement, a more precise definition of what these highly evolved systems are and what attributes they possess has certainly emerged. However, there are still areas in the study where the topic can be advanced by a more rigorous presentation of the basic elements. One such area is the taxonomy of systems-of-systems. This paper will begin with the definition of systems-of-systems as it currently stands and will present the taxonomy from a broader view with additional considerations for classification. These taxonomic categories will consider dimensions in the classification of systems-of-systems based on their acquisition strategy, operational mode, and problem domain with examples in each case.

Introduction

Systems engineers strive to understand the requirements, architectures, principals, management, and processes used in developing complex systems. As with many other scientific fields this understanding begins with the taxonomy of the elements; in this case the taxonomy of systems-of-systems. The taxonomy is simply an orderly classification of systems-of-systems according to their presumed attributes and relationships. A clearly defined classification scheme is essential in developing common systems engineering architectures and methodologies. For example, the approach used to build a network-centric C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance) system may be insufficient or even incompatible for building a public transportation system. Both can be considered a system-of-systems, but each is amply different from the other that an alternate approach to the engineering process is usually required. However, the approach used to build one network-centric C4ISR system may be very similar or even identical for building any network-centric C4ISR system, just as the approach used to build one public transportation system maybe very similar or even identical for building any public transportation system.

Systems

Before exploring the taxonomy, a clear definition of systems-of-systems is needed. This definition begins with that of a system. According to Blanchard and Fabrycky, a system is (Blanchard et al. 1998):

> "…an assemblage or combination of elements or parts forming a complex or unitary whole, such as a river system or a transportation system; any assemblage or set of correlated members, such as a system of currency; an ordered and comprehensive assemblage of facts, principles, or doctrines, in a particular field of knowledge or thought, such as a system of philosophy; a coordinated body of methods or a complex scheme or plan of procedure, such as a system of organization and management; any regular or special method of plan of procedure, such as a system of marking, numbering, or measuring."

Simply put, a system is a combination of dependent elements operating together to accomplish a single common goal. The system cannot be expected to operate in the designed manner without its components and the components serve no useful purpose when separated from the system (see Figure 1).

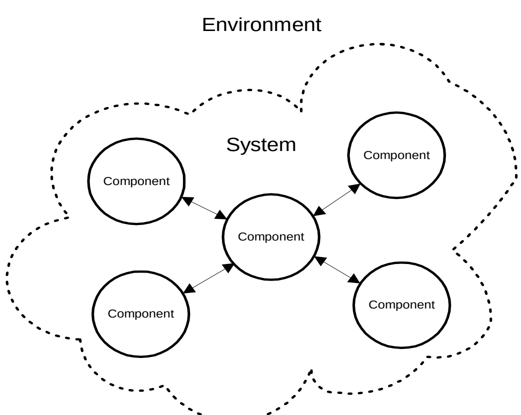

Figure 1. A System, its Components, and the Environment

Several dichotomies exist to classify systems. There are *natural* and *artificial* systems, *physical* and *conceptual* systems, *static* and *dynamic* systems, and *open* and *closed* systems (Blanchard et al. 1998). The natural systems differ from the artificial systems in that they exist in nature, where as artificial systems are man-made. Physical systems differ from conceptual systems in that they operate in the physical environment on matter or from matter, whereas conceptual systems exist abstractly as ideas, plans, or information. Static systems differ from dynamic systems in that they are fixed and do not change, whereas dynamic systems continually change. Open systems differ from closed systems in that they interact with their environment through a boundary, where as closed systems do not.

Systems-of-Systems

The definition of a system-of-systems can be built upon that of a system. A system-of-systems is different from a typical system in that the components of the system are themselves systems. According to Maier the term systems-of-systems (Maier 1999):

> "…as commonly used, suggests assemblages of components that are themselves significantly complex, enough so that they may be regarded as systems and that are assembled into a larger system."

Additionally Maier and Rechtin define two characteristics that systems-of-systems must possess (Maier et al. 2000): "

1. Fulfil valid purposes in their own right, and continue to operate to fulfill those purposes if disassembled from the overall system
2. Are managed (at least in part) for their own purposes rather than the purpose of the whole; the component systems are separately acquired and integrated but maintain a continuing operational

existence independent of the collaborative system."

This can be summarized as, a system-of-systems is a system built from independent systems that are managed separately from the larger system. With this definition, it should be clear that systems-of-systems form a subset of systems (see Figure 2).

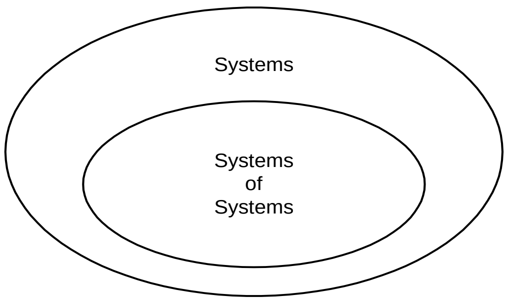

Figure 2. Systems-of-Systems Venn Diagram

In a system-of-systems the component systems produce some utility that is greater than the sum of the individual component systems. But when separated the component systems still serve some useful purpose. Considered as single entities the component systems, by definition, typically interact with both the environment and each other (see Figure 3).

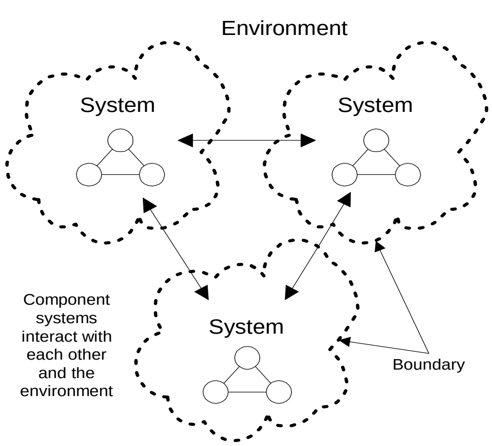

Figure 3. A System-of-Systems and the Environment

Systems-of-systems have different characteristics than those of typical systems. According to Maier, systems-of-systems usually possess five unique properties that set them apart from systems (Maier 1999):

1. Operational Independence of the Components
2. Managerial Independence of the Components
3. Emergent Behaviour of the System
4. Geographic Distribution of the Components
5. Evolutionary Development of the System.

Given the definition and characteristics of systems-of-systems the discussion of the classification of such systems can proceed.

The Taxonomy

Though systems-of-systems are a subset of systems, the dichotomies of classification for typical systems cannot be easily applied to systems-of-systems. Systems-of-systems are almost exclusively man-made, dynamic, and open systems. It is for this reason that a separate taxonomy is needed for systems-of-systems. The following sections will examine the taxonomy issue with regards to the acquisition, operation, and domain of systems-of-systems. This examination will consider the broader picture of the research that has been done in the taxonomy of systems-of-systems.

Acquisition Classification

Systems-of-systems can come into being for different reasons. In some cases these systems are planned, but in other cases they are unplanned (unplanned in the sense that when the component systems were acquired their integration was not anticipated). This observation was recognized by Allison and Cook (Allison et al. 1998). They classified systems-of-systems, based on how they are acquired, as either *dedicated* or *virtual.* This distinction can be important in determining how much effort is required to engineer the interaction between the component systems and achieve the system-of-systems concept.

Dedicated Systems of Systems. The dedicated systems-of-systems are those that are consciously designed and engineered from the beginning to be systems-of-systems. Interaction between the component systems is, to a certain extent, expected when the systems are acquired. Additionally, these systems-of-systems generally function as larger systems, with component systems working together, for the duration of their entire existence.

In the past many military systems-of-systems were not acquired in this manner. However, the emerging trend is to design military systems around the systems-of-systems concept. The Future Combat Systems program currently being pursued by the U.S. Army is an excellent example of a dedicated system-of-systems (http://www.army.mil/fcs). The goal of this program is to acquire several ground, air, and soldier systems linked together via a communications network. Indeed the system may grow and evolve, but the key here is that the larger system has been planned and designed around the systems-of-systems paradigm.

Virtual Systems of Systems. Virtual systems-of-systems differ from dedicated system-of-systems in that their acquisition is generally unplanned when the component systems are engineered and acquired. As Cook notes (Cook 2001):

> "…these [systems-of-systems] take forms that are rarely envisaged at design time and that they frequently comprise elements that were never designed to be integrated."

Another characteristic of these systems is that once their use has ended the component systems are usually disassembled and no longer operate as a part of a larger system-of-systems.

Examples include military systems-of-systems where existing systems that were never designed to interface with one another are integrated in a very short time period to satisfy an emerging need. Cook provides the example of a C2 (Command and Control) system for military operations involving a coalition of nations (Cook 2001). The system-of-systems exists for the duration of the operation and is discontinued once the operation has concluded. The advantage of this merger is that the coalition can more effectively command the operation than could the participating nations acting individually. The important point here is that the individual command and control systems were not originally planned to operate as a larger system-of-systems.

Operational Classification

The managerial style of systems-of-systems can vary greatly. This observation can be used to classify systems-of-systems based on the way in which they operate and on how the component systems interact with one another. One such classification scheme defined by Maier includes three classes of systems (Maier 1999); *virtual* (chaotic), *directed*, and *collaborative*. Here the term *chaotic* will be used instead of *virtual* to differentiate it from the usage chosen by Allison and Cook (Allison et al. 1998) to describe a system-of-systems whose acquisition, at least initially, is unplanned.

Chaotic Systems of Systems. In chaotic systems-of-systems there is no central control authority or managerial entity and thus no agreed upon purpose. The purpose is neither designed in nor expected in many cases. The component systems operate completely independent of each other and the function of such systems as a system-of-systems is often random and unpredictable. Emergent behavior exists on a large general scale and the system relies on intangible mechanisms for operation. These systems might also be called virtual (Maier 1999) systems-of-systems since they seem to operate via invisible mechanisms.

The open source software application development system is one example of a chaotic system-of-systems (Selberg 2002). This is a system of software development in which individual software developers contribute to the development of a software application. For a given application developers implement software modules in a manner they determine as appropriate. There is little control on how each individual implements a module. The individuals act under their own authority when designing and implementing software elements. When the software modules are submitted for inclusion into the application other developers have the opportunity to review and modify the module. The individual developers are the component systems and the development project is the larger system-of-systems. The process of development is essentially chaotic and unpredictable since there is little or no control over each developer and because there is no specific plan of the functionality to include in a project. The advantages of such a system are that many diverse ideas are considered and that constant and continual review results in a higher quality application.

Directed Systems of Systems. The directed systems-of-systems are controlled by a central management authority. They are designed and operated for a specific purpose. The component systems still operate relatively independently; however, at the highest level their operation is predetermined. These systems differ greatly from chaotic systems because their behavior is, at least somewhat, predictable and the interaction among component systems is directed by some managerial influence. These systems may also be referred to as coerced systems-of-systems.

One example of directed systems-of-systems is the network-centric warfare systems. These systems are managed, for the most part, by military command centers. The network-centric systems integrate intelligence systems, ground and air warfighter systems, and communication systems together through networked information sharing capabilities. Each component system is capable of carrying out missions independently of the other systems, but does so more effectively as a component of the larger system and for the higher purpose. Capabilities of these systems, as with all systems-of-systems, are constantly being added, removed, modified and enhanced through experience.

Collaborative Systems of Systems. In collaborative systems-of-systems the component systems interact voluntarily almost out of necessity. Any management authority has little power to coerce the behavior of the component systems. Management authorities may issue standard practices and procedures by which components must operate to be a part of the larger system, but ultimately it is up to the component systems to acquiesce to those standards to become part of the larger system (as with the Internet). However, the overall behavior of these systems may still be somewhat unpredictable.

One example of a collaborative system-of-systems is the family (Selberg 2002) – though naturally occurring systems are not generally considered in the study of systems-of-systems. Each member of a family is a system in their own right. Each decides for themselves when and how they interact. But by voluntarily interacting the family functions as a system-of-systems with the emergent properties of emotions such as love and new systems such as children. This system is a continually evolving system changing its behavior, structure, and even geographic distribution through time. How the family operates is completely up to the family itself. When the family members collaborate as a single entity the whole is greater than the sum of the parts.

Domain Classification

The problem domain of a system-of-systems is another important classification characteristic to consider when building systems-of-systems. There are many domains where systems-of-systems exist, but these could all be broadly categorized into three divisions. Though no published work was found in the literature specifically concerning the taxonomy of systems-of-systems by problem domain, an approach similar to that for classifying typical systems seems appropriate. Thus the domain classification produces a taxonomy of three divisions; physical, conceptual, and social.

Physical Systems of Systems. Physical systems-of-systems are systems that operate in or on the physical world. This would include systems that involve interactions between humans and the physical world or systems that are completely embedded in the physical world with no human interaction. These systems are composed of component systems that are tangible or affect matter. That is, these systems exist in and occupy physical space. As previously mentioned, in the realm of systems-of-systems most physical systems are man-made rather than natural, though natural systems-of-systems may certainly exist.

One example of a physical system-of-systems is the electrical power grid. This system is composed of relatively independent power generation facilities that include gas, coal, hydro-electric, wind, and nuclear power generation systems. Many different companies operate these facilities, yet all are connected and tied together to form a single power distribution and sharing mechanism capable of providing better service.

Conceptual Systems of Systems. The conceptual systems-of-systems are abstract in nature. They do not exist as tangible entities in physical space nor do they operate on or manipulate matter. Systems that are conceptual include those in which humans interact with concepts or those that require no human intervention at all. These systems mainly represent ideas, plans, concepts, procedures, and hypothesis. Conceptual systems are conceived and utilized but can never actually be “built.” In fact the plans, procedures, and methodologies for engineering physical system-of-systems might of themselves be considered conceptual systems-of-systems.

One example of a conceptual system-of-systems is an intelligence gathering system. There are many techniques for gathering military or political intelligence such as those for obtaining human, signal, and visual intelligence and each is considered a separate system. All may be utilized and even managed independently of the others but when merged together they produce a broader picture not necessarily seen from any single component system. This is different from a physical system-of-systems because physical space or matter is not essential to its operation. Instead, information is the key ingredient.

Social Systems of Systems. Sometimes it does not seem natural to categorize a system-of-systems into either the physical or conceptual classes. For instance many of the socio-political systems that exist contain both physical and conceptual elements, yet are still fundamentally different from each that it may be inappropriate to force classification into either group. An essential difference is that the main form of interaction is between people or organizations utilizing policies and procedures.

One example of a social system-of-systems is government. Governments exist, by definition, to rule people and provide control over a sovereign nation. Governments consist of many branches, bureaucracies, organizations, and agencies all operating under the jurisdiction of doctrines or constitutions and existing at different levels of jurisdiction (city, county, state, and federal levels) for the purpose of governing people and resources. Each of these components is a system within a larger governing system. The component systems interact in complex often random ways but the utility of the whole is greater than the sum of the parts.

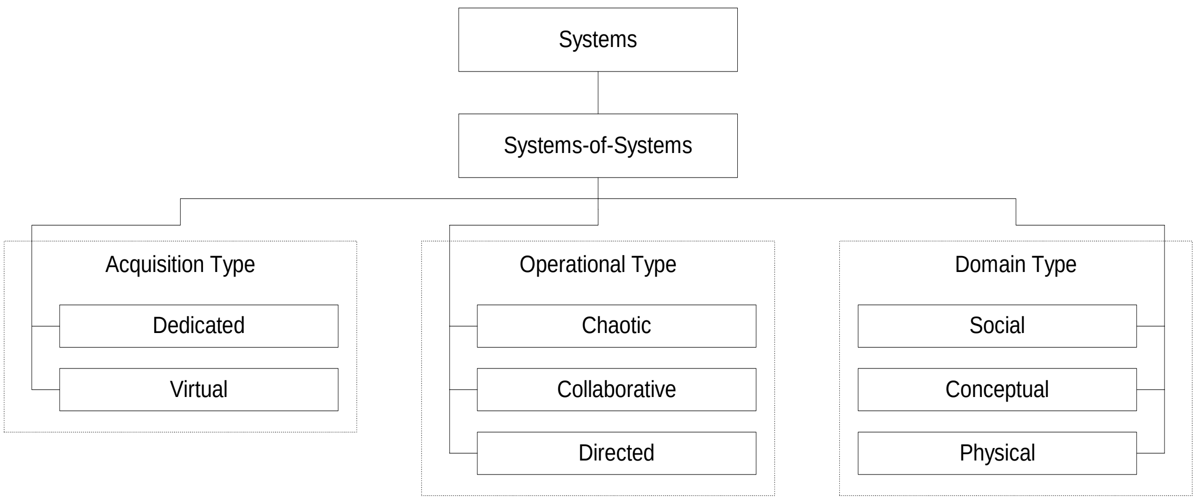

Figure 4. Taxonomic Summary

Conclusions

Systems-of-systems are a collection of independently useful systems where the whole is greater than the sum of the parts; have emergent properties and behaviors that are not necessarily designed in nor expected; and continually evolve with new functionality added, removed, and modified through time and with experience. Systems-of-systems are acquired and operate in different ways and exist in different problem domains. These characteristics can be used to classify the systems into different categories forming a more concise taxonomy (see Figure 4). However, the taxonomy summarized in this paper may not be complete or even necessarily correct. Given this observation and the realization that systems-of-systems science is a new and emerging field, it may be appropriate to examine the taxonomy of systems-of-systems in more depth while leveraging more specific and detailed examples and higher taxonomic dimensions.

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Biography

James Gideon is a Senior Embedded Software Engineer at The Boeing Company's Phantom Works organization where he has worked for over 5 years. He has a BS degree in Computer Science from Southwest Missouri State University and a MS degree in Systems Engineering from the University of Missouri - Rolla. His research interests include topics in software architecture and development, reinforcement learning, neuro-dynamic programming, and network-centric systems. He can be contacted at james.m.gideon@boeing.com.

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