Architectural Patterns for Self-Organizing Systems-of-Systems

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Abstract. Contemporary threats exhibit unique characteristics that challenge classical security systems. In response to these threats, the DoD has an increased focus on applying proven SE techniques to SoS, which provide more functionality and performance than the sum of the constituent systems. Tools and techniques are necessary to facilitate evolution of today's systems. One major need is the ability to develop agile SoS architectures that respond to contemporary threats. This paper focuses on one characteristic of contemporary threats, self-organization. Different SoS are reviewed for the driving forces that support their self-organizing architecture. Necessary characteristics are identified and general constructs are put forward as candidate architectural patterns. These candidate patterns are now available for evaluation and employment consideration. They can be applied when problems common to the pattern manifest in new environments. They also add to the body of knowledge for SoS SE.

Introduction

In an attempt to better address the needs of the war fighter, the Department of Defense (DoD) has an increased focus on an evolutionary delivery of capability (DOD 2003). An incremental approach delivers capability quickly, while preserving the ability to improve capability over time. The success of this approach is dependent on a phased capability definition and the successful deployment of systems that provide increasing capability over time (DOD 2008a Fig 2). In conjunction with this movement, the DoD also has an increasing interest in Systems-of-Systems. In 2006, the Under Secretary of Defense for Acquisition and Technology charged the Systems and Software Engineering Directorate to develop a guide for Systems Engineering for Systems-Of-Systems (SoS) resulting in (Systems Engineering Guide 2008). This action recognizes the advantages of System Engineering principles in successful system acquisition and the ability of Systems-of-Systems Systems Engineering (SoS SE) to address the dynamic threat situation in today's world.

The SoS guide identifies seven core principles upon which the application of SoS SE are dependent (DOD 2008b, 17-20). Two of these principles are of particular interest in this paper. The first is developing and evolving an SoS architecture. The guide indicates that the architecture of an SoS addresses the concept of operations for the SoS and encompasses the functions, relationships, and dependencies of constituent systems, both internal and external. The guide points out that a key aspect of the architecture must address evolution of the SoS. The second principle, which is closely related, is monitoring and accessing change due to influences outside the control of the SoS.

Dove (Dove 2010) discusses challenges facing contemporary security strategies, indicating that attack communities operate as intelligent, multi-agent, self organizing, systems-of-systems – with swarm intelligence, tight learning loops, fast evolution, and dedicated intent. His research includes an agile system framework based on the characteristics: self-organizing, adaptable, reactive, evolving, proactive, and harmonious. These are identified through the acronym SAREPH, based on the first letter of each characteristic. In this work self-organization is called out as the most important and necessary characteristic. This paper explores the aspect of self-organization further.

Self Organization

Definition

So what is self-organization? Azani (Azani 2009) describes self-organization as a process where a system undergoes increased order where internal organization becomes more complex all without outside intervention. Camazine et al. (Camazine, et al. 2001) define self-organization as the emergence of pattern at the global level caused purely from interactions at the lowest components based on local information.

Heylighen (Heylighen 2008) describes self-organization as the generation of global structure resulting from positive and negative feedback of local interactions of independent agents. The goals of each agent contribute to the preference of the collection. Compromises have to be made, but an ultimate state of stability is reached, which maximizes the utility of the group. The group then exhibits emergent behavior, where the function or organization of the whole is greater than the function of the individuals. When the influences (internal or external) change, the collection is disrupted and must reorganize to reach the next stable state.

At its very core, self-organization allows an entity to adapt its structure to fit its environment. Every situational scenario to which an entity is exposed cannot be foreseen at its creation. However, self-organization determines the entity's freedom to respond to those situations (Azani 2009). But what guides this freedom? On what principles does an entity make organizational change? What is its motivation? The answers to these questions come from an understanding of the necessary characteristics.

Self-organizing Characteristics

Other studies (De Wolf and Holvoet 2004) have identified characteristics which result from self-organization. The resulting characteristics include examples of increased order, but they do not directly address what allows self-organization to happen. Comparisons of SoS, for this paper, focus on a set of characteristics or traits that appear to form a necessary basis for self-organization in SoS (Nichols 2010). While these traits were identified as a result of reviewing self-organizing SoS, they are presented first so that their appearance is clear in the reviews of specific SoS later in this paper. Following the review of several SoS, these characteristics are revisited to show that they are necessary for self-organization to occur.

Common Purpose

Abraham Maslow proposed a theory on human motivation based on a hierarchy of needs (Maslow 1943). At the base of the hierarchy are the physiological needs; these are the most primitive needs for all organisms based on self preservation. Some correlate these needs to homeostasis, the maintenance of a constant stable internal state (Azani 2009). At the top of the motivation hierarchy is self-actualization. Maslow describes this motivation as a person achieving potential (Maslow 1943). Satisfaction of needs at any level in the hierarchy, according to Mazlo, must pass a threshold before concern is directed to higher levels.

All self-organizing SoS have some basic needs that must be satisfied for the SoS. These are the reason the SoS was established. The purpose of each individual system contributes to satisfy those primitive needs of the SoS. As these needs are satisfied, emergent characteristics start to manifest. The SoS develops a higher meaning for existence, which crystallizes as the SoS evolves. This common purpose provides motivational direction for the constituent systems. The clearer the purpose is, the stronger the characteristic of *belonging* (Boardman and Sauser 2008) becomes.

Conditional Dependency

Ashby (Ashby 1962) describes organization as requiring dependencies between all components. When the relationship between two systems A and B is conditionally based on a third system C, Ashby indicates that “a necessary component of organization is present”.

This does not mean that every system is connected to every other system as in the context of a mesh network. It simply means that the SoS relevant actions/behavior of one system somehow influence the behavior of all other systems. These influences may not be direct; but rather indirect manipulations of the behavior of one or more intermediate systems.

A self-organizing SoS must exhibit conditional dependency; the constituent systems must be connected.

Situation Awareness

Situation awareness has its roots in aviation (Endsley 2000) and is normally associated with human operators (e.g. pilots). However, the general concepts are applicable to self-organization, whether humans are included or not. Situational awareness requires comprehension of environmental forces and understanding how behavioral actions may influence goals or objectives. It requires understanding the important things happening within a given space and time. Endsley identifies three levels in situation awareness (Endsley 2000, 3-4). The most basic of the three is perception, which involves monitoring the environment and recognizing relevant situational elements. Level two is the correlation of those elements and understanding how they influence objectives. The last level allows for projection of future action or predicting how the environment might change.

Endsley is careful to point out that situation awareness is distinct from and a precursor to decision making and performance (Endsley 2000, 5). Poor decisions can occur with ideal situation awareness, and conversely ideal decisions can be made without any situation awareness. After the decision is made, action must occur. Situation awareness, decision making, and performance form a cycle; but, situation awareness is simply having a clear understanding of current events in a given space and time.

Adaptable

Dictionary.com defines adaptable as being readily capable to adjust to different conditions. In practice, this means that an entity can reorganize its resources based on current needs (Dove 2010).

A dynamic environment is a given; SoS do not find themselves in an unchanging domain. This is why monitoring and assessing change is a core element for SoS SE (Systems Engineering Guide 2008 54). Self-organizing SoS must have a sufficient set of behaviors to respond to change. In extreme cases, failure or attack may cause constituent systems to be damaged or completely fail. An SoS must be able to maintain or mutate internal structure autonomously in the face of change (De Wolf and Holvoet 2004). It is this characteristic that allows self-organization to support evolution.

Autonomy

Autonomy is the ability to make independent decisions (Boardman and Sauser 2008). Autonomy requires that there must be no outside influence or control (De Wolf and Holvoet 2004, 8). It is worth mentioning that the context of a system is important. For example, a group of stakeholders may hold the decision making capability. In those situations, the context must include those stakeholders within the SoS. If those same stakeholders are considered outside of the context, then autonomy is lost.

For autonomy, it is only imperative that the controlling component(s) be considered a part of the SoS. According to (Dove 2001, 146-148) agility is increased when that autonomy is distributed throughout the constituent systems. Each constituient system is allowed to change its behavior based on its independent observations. This is opposed to the characteristics of a single system, whose components are required by design to react based on direction or a priori rules of engagement.

Whole-Part Relationship

An additional characteristic deemed necessary for self-organization is that of the whole-part relationship (Ashby 1962). The definition of organization calls for interconnected parts. SoS inherently fit this criteria. The whole is the SoS, and the components are the constituent systems. Thus, an SoS inherently satisfies the whole-part aspect of the definition of self-organization, and will not be shown in the tables that follow.

System-of-Systems

The Defense Acquisition Guidebook (DAG) chapter on Systems Engineering (Ch 4) defines a system of systems as “a set or arrangement of systems that results from independent systems integrated into a larger system that delivers unique capabilities” (Defense Acquisition Guidebook 2010). Boardman and Sauser go on to identify five essential characteristics of SoS: autonomy, belonging, connectivity, diversity, and emergence (Boardman and Sauser 2008, 155-161). Each of the constituent systems has its own reason to exist and unique capabilities to perform (autonomy). The SoS must provide a reason for constituent systems to participate (belonging). The constituent systems must be able to interact with and adapt to each other and their environment (connectivity). The law of requisite variety demands that the interior diversity between systems must match the variety of the environment the SoS faces (diversity). And an SoS must have agility to respond to its environment thus presenting capabilities the constituent systems do not exhibit independently (emergence).

Each individual system has an independent purpose, which was specified when the system was developed. If the stakeholders of that system identify complementary capabilities in another system, organizational relationships are formed and the systems are linked together. A higher level purpose is satisfied. This process continues until a collection of systems becomes classified as an SoS. The resulting SoS has synergy generated from the constituent systems and emergent behavior, which is not present in the separate contributors.

An SoS must be organized, even if that organization is ad hoc. The inter-working agreements between systems establish order and define the whole-part relationships. The reason the constituent systems came together was to satisfy some common purpose. And, their connected interfaces instantiate conditional dependencies. Thus, an SoS clearly satisfies three of the six characteristics identified for self-organization.

Boardman and Sauser use autonomy in the context of a constituent system's independent existence. Some stakeholders and various parts of the constituent system may fall outside of the scope for the SoS; therefore, it may not directly support the organizational needs of the SoS. On the other hand, the autonomy of the SoS is directly supported when the constituent system's decision making influence does fall inside the context of the SoS.

Adaptability is an agile concept. Developing an adaptable system or SoS may be a preferred methodology, yet it is conceivable to build a rigid/static SoS. The lifetime of the SoS is likely to be much shorter than one that can adapt. Nonetheless, the resulting rigid SoS may satisfy a tactical need. Or, it may just be a product of short sighted stakeholders. So, an SoS does not necessarily need to adapt.

That leaves the question regarding situation awareness. As already discussed, decisions can be made in the absence of situational awareness. An SoS presents no demanding basis for situational awareness, and situational awareness does not bring about an SoS.

Thus, an SoS is not in itself sufficient for self-organization to exist. An SoS does not need adaptability, autonomy, or situation awareness. Self-organization is an enhancement to an SoS.

Self-organizing SoS

In the following discussion several SoS are examined for their self-organizing feature. The reason each SoS needs the self-organizing capability is identified along with the approach taken to implement it. Since each example is considered to be an SoS, the whole-part relationships are not identified in detail; but, the remaining five self-organizing characteristics are identified in each case.

Ushahidi

Following the presidential election in Kenya 2007, there was an economic, political, and humanitarian crisis that developed (Wikipedia n.d. 2007-2008 Kenyan crisis). The incumbent president Mwai Kibaki was declared the winner in December of 2007. However, there were claims that the election had been manipulated in Kibaki's favor. What started with non-violent protests, led to rioting, targeted ethnic attacks and general anarchy. This violence had high visibility in the media.

Ory Okolloh, a prominent Kenyan lawyer, voted in the December election (Giridharadas 2010). After seeing the unrest, she posted the idea of an Internet mapping tool to allow anonymous reports of violence. A small group of developers built the resulting web site, Ushahidi, over a long weekend. Ushahidi, which means "testimony" in Swahili, allows individuals to report situations via SMS, email, or web; subsequently the information is correlated for display on a map or timeline (About Ushahidi n.d.).

Kenya presented a problem where crisis reporting was necessary. Within a few days, violence was prevalent and the deployment of reporters into the region was not practical. Crowd sourcing was used to solve the problem. The population in a crisis center is enabled to report events without any further direction or guidance. A self-organizing group of volunteers takes the data reported and correlates it to a map. From there, observers utilize the data to provide relief.

Table 1: Ushahidi self-organizing characteristics

Self-organizing Characteristic	**Ushahidi**
Common Purpose	• Crisis support • Initially to track incidents of violence
Conditional Dependency	• Events reported by local observers • Events verified by volunteers • Relief provided to victims
Situation Awareness	• Local observers report via SMS, email or web • Correlated events reported via web
Adaptability	• Any event can be reported; observer selected • Adapted to any crisis e.g. 2010 Gulf spill (Sutter 2010)
Autonomy	• Local observers decide when and what to report • New deployments take minimal time
Whole-Part Relationship	• Inherent in SoS

Swarm Robotics

A robotic swarm is a large group of small robots, each of which performs a relatively simple task. However, the aggregation of the swarm exhibits emergent behavior that is much more complex. Member robots exhibit independent decisions or intelligence (Sahin 2009). The culmination of those decisions supports the mission objective of the swarm. Sahin describes an example robotic swarm design used to locate and disarm mines in minimal time. By definition, the swarm has a common purpose.

Encounters in the environment, detection of a mine, by one robot influence the actions of other robots. Thus, there is conditional dependency between the robots. These dependencies are relayed via two types of messages under ant-colony based algorithms: short-range recruitment (SRR) and long-range recruitment (LRR) (Sahin 2009, 483). Ants signal these situations using pheromones; however, robots may use RF messaging to communicate these messages. The mine detection swarm has a well defined communication framework (Adaptive Time Division Multiple Access or ATDMA) that the robots must follow (Sahin 2009, 494). When a mine is detected, a message is transmitted to nearby robots, which trigger them to follow. When a sufficient number of robots are near the mine, they collectively disable the mine. Once the mine is disabled, the robots resume their independent foraging.

Table 2: Swarm Robotics self-organizing characteristics

Self-organizing Characteristic	**Swarm Robotics**
Common Purpose	• Locate and disarm all mines in a given area
Conditional Dependency	• Operational behavior or rules of engagement; robots must respond to recruitment messages
Situation Awareness	• Short Range Recruitment messages • Long Range Recruitment messages
Adaptability	• Robust with respect to individual robot failures
Autonomy	• Independent robotic decisions; robots randomly search and independently respond
Whole-Part Relationship	• Inherent in SoS

Self-organized Learning Environments

Sugata Mitra studies the concepts of self-organized learning (Mitra 2010). He started experimenting in 1999 with what later became the Hole in the Wall project (Hole in the Wall 2009). In this experiment, Mitra placed a computer with high-speed Internet into the wall of a slum in New Delhi. An 8-year old boy taught himself and a 6-year old girl how to browse the Internet. Mitra repeated similar experiments in various villages throughout India. The conclusion was that groups of children can learn how to use computers and the Internet on their own, regardless of their background education. Mitra quotes Arthur C. Clarke saying "if children have interest, education happens".

Refinements led to a testing exercise in Gateshead, UK. Mitra provided computers and asked thirty two children to get into groups of four. There was no formal teacher. He allowed the children to change groups, observe other groups, and talk to other groups. However, each group of four was restricted to a single computer. The children were given an exam of six questions. All of the groups had completed the exam in 45 minutes or less, with an average score of 76 (Mitra 2010).

Next, Mitra asked for grandmother volunteers. Their only commitment was to have a broadband Internet connection. They were asked to mediate learning environments in remote locations. The initial invitation brought 200 volunteers. The children referred to these volunteers as the "Granny Cloud". His research ultimately led to the development of a Self-Organized Learning Environment (SOLE) (Davidson 2010; SOME Team n.d.).

Table 3: Swarm Robotics self-organizing characteristics

Self-organizing Characteristic	**SOLE**
Common Purpose	• Topic of interest • Human curiosity
Conditional Dependency	• Small Groups • "Granny Cloud" • Peer pressure
Situation Awareness	• Computer/Internet
Adaptability	• Internet makes any educational topic possible • Children self-organize small groups "at will"
Autonomy	• Children decide how to learn
Whole-Part Relationship	• Inherent in SoS

Self-organizing Patterns

The following discussion looks back at the SoS examples examined and extracts potential patterns for self-organization. For each recommendation, the key pattern attributes are identified: name, context, problem, forces, solution, and examples (Nichols 2010).

Crowd Sourced Incident Reporting

Table 5 identifies the Crowd Sourced Incident Reporting pattern, inspired by the Ushahidi SoS. Crisis environments are dangerous for reporters to explore. The number of incidents within the environment can be significant; therefore, it is not practical for a small group to witness most incidents first hand. The individuals within the population of the crisis environment are already there. They are firsthand witnesses just by being there. Thus, it is a reasonable next step to leverage those individuals to provide their testimonies. A broadcast announcement is made using mass media that informs the population on how to submit firsthand testimony. Individuals then take on the responsibility to report incidents, which they deem relevant. All of the testimonies are collected, in the case of Ushahidi, in a web based database.

Another example: Many local police organizations have adopted AMBER Alerts to enlist the public at large when a child abduction occurs, broadcasting the information to subscribers as well as posting information publically. Originally named for Amber Hagerman, a 9-year-old child who was abducted and murdered in Arlington, Texas, broadly used AMBER now refers to the backronym *America's Missing: Broadcasting Emergency Response.*

Table 4: Crowd Sourced Incident Pattern

Name	Crowd Sourced Incident Reporting
Context	Incident information is needed from a large population potentially scattered across a broad geographic area.
Problem	Details of a crisis event are needed, but sending in a team of specialists does not scale and they are subject to the crisis at hand.
Forces	• Individuals within the population decide what to report, but their reports may not be relevant or accurate. • Succinct relevant information is desired but unconstrained reporting resources leads to numerous reports. • Full coverage is desired but the geographic area may be vast and hostile.
Solution	Create the ability for the population within the crisis zone to submit first hand witness reports and support the ability to correlate the data.
Examples	• Ushahidi (Giridharadas 2010) • Citizens monitor Gulf Coast after oil spill (Sutter 2010) • Amber Alert (Wikipedia n.d.)

Swarm Discovery and Cooperation

Table 7 identifies the Swarm Discovery and Cooperation pattern, inspired by ant foraging activities with similarity in robotic-swarm mine detection. A robotic swarm is built using large numbers of robots, each with relatively simple capabilities. The mass numbers used in swarms allow for parallel activities in time consuming tasks such as searching a vast space. Once target objects are located, robotic swarms, like ants, then self-organize to combine forces in action appropriate to the object (e.g., disarm or transport).

Table 5: Swarm Discovery and Cooperation Pattern

Name	Swarm Discovery and Cooperation
Context	One or more objects of interest must be located in a sparse environment, and the mission objective cannot be accomplished effectively by any one individual.
Problem	Locate objects in a sparse environment and perform some cooperative operation on them (e.g. transport or disarm).

Forces	• Time pressure to accomplish mission vs. cost of multiple resources. • Time pressure to find an object vs. search area size. • Risk of search-agent loss vs. cost of redundancy.
Solution	Randomly deploy a large number of simple agents across the target space. Each agent searches for the object of interest, which can be detected using individual sensors. Once found, the discovering agent notifies others to assist in actions on the target.
Examples	• Mine detection (Sahin 2009) • Multi-agent search & transport (Rodrıguez and Reggia 2005) • Search and rescue • Foraging ants (Traniello 1989, Bollazzi and Roces 2011)

Collaborative Learning

Table 8 identifies the Collaborative Learning pattern, inspired by the self-organizing learning environments called SOLE described by (Mitra 2010). A group of individuals are tasked with learning a new topic and provided only a computer with broadband Internet access. The members are allowed to self-organize into small groups, and the groups are allowed to collaborate and/or compete. The groups take advantage of every member's strengths, and learning is accelerated.

Table 6: Collaborative Learning Pattern

Name	Collaborative Learning
Context	A group of individuals, potentially uneducated, need to learn a new topic. They need to be motivated to overcome perceived hindrances. They have access to fundamental tools (e.g. computer and Internet) to complete the objective.
Problem	A group of individuals are tasked, or take initiative, to learn a specific topic without explicit educational instruction.
Forces	• Peer collaboration in conflict with peer competition. • Natural human learning curiosity vs. availability of learning objectives and situational exposure. • Teacher expertise vs. shortage of teachers.
Solution	Small teams (3-4) with a common learning interest obtain, or are given, access to necessary tools (e.g., Internet search). Mediators may be accessible to assist and answer questions, though not necessarily expert on the topic.
Examples	• SOLE (Mitra 2010, SOME Team. n.d) • Hole in The Wall (Hole in The Wall 2009) • Teaching methods (Davis 1993, Davidson 2010)

Conclusions

This paper began with a background on why self-organizing SoS behavior is important, especially to current DoD acquisitions. Then, a foundation was established for characterizing self-organization from several definitions.

From a review of the literature this paper suggests a novel aggregation of six characteristics that appear to be necessary for self-organization in systems of systems: common purpose, conditional dependency, situation awareness, adaptability, autonomy, and whole-part relationships. These six characteristics were then identified in three self-organizing systems of systems to show how they manifest: Ushahidi, swarm robotics, and self-organizing learning environments. Then characteristics were extracted and abstracted from these examples to develop three self-organizing behavior patterns according to the SAREPH pattern form.

These pattern abstractions add three new candidate patterns to the SAREPH pattern language, an early stage project intending to offer general pattern concepts that might inform purposeful self-organizing system-of-system design activity. Further work is needed in both refinement and ratification of these four candidate patterns as well as in adding appropriate new candidate patterns to the SAREPH pattern language.

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