Architectural Patterns for Self-Organizing Systems-of-Systems

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Contemporary threats exhibit unique characteristics that challenge classical security systems. In response to these threats, the US Department of Defense has increased its focus on applying proven systems engineering techniques to systemsofsystems, which provide more functionality and performance than the sum of the constituent systems. These tools and techniques are necessary to facilitate the evolution of today's systems. One major need is the ability to develop agile SoS architectures that respond to contemporary threats. Here I focus on one characteristic of contemporary threats—self-organization. This article will analyze two different systems-of-systems, one providing security and one attacking security, looking for the driving forces that support their self-organizing architecture. We will begin by identifying the necessary characteristics and general constructs as relevant to architectural patterns.

Self-Organization

So what is self-organization? Self-organization implies a dynamic system composed of components whose relationships reorganize in response to situational forces and events. Azani (2009) describes self-organization as a process where a system undergoes increased order, and where internal organization becomes more complex all without outside intervention. And 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.

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. Self-organization determines the entity's freedom to respond to those situations. But what guides this freedom? On what principles does an entity make organizational change? What is its motivation? I attempt to answer these questions by identifying necessary characteristics covered more thoroughly by Nichols and Dove (2010).

Whole–Part Relationship

The first characteristic that is necessary for self-organization is that of the whole–part relationship. The components must belong to something bigger, where the whole is more than the sum of the parts.

Conditional Dependency

There must also be dependencies between the components. Not every component needs to be directly connected to every other component. However, there must be a traceable path of dependency interconnecting all elements.

Common Purpose

Each constituent part has independent reasons for existence. As those needs are satisfied, the parts must be motivated to fulfill a higher-level objective. This higher-level objective is the common purpose that binds the pieces together into the whole.

Autonomy

The *self* in self-organization requires that any decision-making authority must lie within the context under consideration. Organizational decisions must not have any outside influence.

While the context may be somewhat subjective, it is important in determining if autonomy is present.

Situational Awareness

Situational awareness has its roots in aviation, but the general concepts are also applicable to self-organizing systems. A self-organizing system must perceive environmental forces and the impact the forces may have on mission objectives. Situational awareness requires understanding the important things happening within a given space and time.

Adaptability

A dynamic environment is a given, which is why monitoring and assessing change is a core element for system-of-systems engineering (US Department of Defense 2008, 54). Self-organizing entities must have a sufficient set of behaviors to respond to change. A self-organizing entity must be able to reconfigure, add, or remove resources in response to situational forces.

System of Systems

A system of systems comprises a set of independent systems, having complimentary behavior, that combine together to generate unique emergent capability. Boardman and Sauser identify five essential characteristics of systems-of-systems: autonomy, belonging, connectivity, diversity, and emergence (Boardman and Sauser 2008, 155–161).

Every 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. Further, their connected interfaces instantiate conditional dependencies. Thus, an SoS clearly satisfies the first three characteristics 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. Autonomy can be lost, while the SoS remains intact. Adaptability is an agile concept. Developing an adaptable system or SoS may be a preferred methodology, yet it is conceivable to build a rigid or 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. An SoS does not necessarily need to adapt. Right or wrong, 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 situational awareness. Self-organization is, however, an enhancement to a system of systems.

Examples of Self-Organizing Systems-of-Systems

We now present two security-related examples of systems-of-systems with self-organizing characteristics. We will highlight the self-organizing architectural pattern applicable to each.

Ushahidi

Following the presidential election in Kenya 2007, there was an economic, political, and humanitarian crisis. The incumbent president Mwai Kibaki was declared the winner in December 2007. However, there were claims that the election had been manipulated in Kibaki's favor. What started with nonviolent protests, led to rioting, targeted ethnic attacks, and general anarchy. This violence was given high visibility in the news media.

Ory Okolloh, who voted in the December election, posted the idea of an Internet mapping tool to allow anonymous reports of violence (Giridharadas 2010). A small group of developers built the resulting website, Ushahidi, over a long weekend. Ushahidi, which means "testimony" in Swahili, allows individuals to independently report situations. Subsequently, the information is correlated for display on a map or timeline.

Table 1. Self-organizing characteristics of Ushahidi

Self-Organizing Characteristic	**Ushahidi**
Whole–Part Relationship	• The whole is the crisis situation, including Ushahidi • The parts include members of the population, the protestors/rioters, the Ushahidi software, the volunteers, and any potential relief workers
Conditional Dependency	• Events reported by local observers • Events verified by volunteers • Relief provided to victims
Common Purpose	• Crisis support • Initially to track incidents of violence
Autonomy	• Local observers decide when and what to report • New deployments take minimal time
Situational Awareness	• Local observers report via SMS, email, or web • Correlated events reported via web
Adaptability	• Any event can be reported; observer-selected • Adaptable to any crisis; e.g., 2010 Gulf of Mexico oil spill

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. Crowdsourced incident reporting (see table 2) was used to solve the problem. With this approach, 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 2.Pattern for crowdsourced incident reporting

Name	Crowdsourced 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 for reporting.
Examples	• Ushahidi(Giridharadas 2010) • Gulf of Mexico oil spill (Sutter 2010) • Amber Alert for missing children in United States (see US Department of Justice website, http://www.amberalert.gov/)

Al Qaeda

Al Qaeda has done much to bring the concept of the self-organizing SoS to public attention. Its organization consists of a collection of loosely coupled terrorist cells that are networked together for the common purpose of establishing a pan-Islamic caliphate and removing the United States from any involvement in Islamic countries (Hazdra 2006).

The emir provides vision and direction to Al Qaeda members. In line with this concept, Osama bin Laden issued two *fatawā*. In the *fatwā*, Osama bin Laden calls for "fast moving light forces that work under complete secrecy"(Laden 1996). He calls for the Islamic youth to employ guerilla warfare against the American-Israeli alliance and carry out jihad. The use of Islam and promise of relief from oppression contributes to a common purpose and conditional dependency for Al Qaeda members.

Both fatawā were initially distributed through fax, as Al Qaeda leverages conventional civilian communication channels. Feedback occurs through the mass media; both successes and failures are highly publicized. Traditional governmental communication mechanisms are handled outside of civilian channels; yet Al Qaeda chooses commercial communication mechanisms, partially because they cannot be destroyed due to impacts on world economy.

Table 3. Self-organizing characteristics of Al Qaeda

Self-Organizing Characteristic	**Al Qaeda**
Whole–Part Relationship	• The whole is Al Qaeda, its members, and everything Al Qaeda represents • The parts are the cells, which include the members
Conditional Dependency	• Sworn allegiance • Relief from oppression • Medical benefits
Common Purpose	• Pan-Islamic caliphate • Islamic jihad

Autonomy	• Autonomous cells

Situation Awareness	• Fatawā
	• Commercial and civilian communications
	  o Fax, cell phones, email
	  o TV, newspapers, magazines

Adaptability	• Dynamic network; changing connections between cells • Robust with respect to loss of any single cell

The cell structure of Al Qaeda supports a distributed decision mechanism. While some cells are linked to the central regime, others are completely autonomous. Each cell is free to organize and make independent decisions as long as the decisions are in line with core beliefs. Al Qaeda epitomizes the clear-cause coordination pattern (see table 4).

Table 4. Clear-cause coordination pattern

Name	Clear-cause coordination
Context	Covert autonomous cellular operations that must avoid detection by the enemy.
Problem	Plan and execute a tactical mission in support of a strategy, but without direct communication or contact with the central coordination.
Forces	• Explicit direction is not available but indirect communication is subject to interpretation. • Overall objectives are large, but cells are too small to address or know all objectives. • Cells may have conflicts between common purpose and selfish motivations.
Solution	Define a common purpose strong enough to bind and motivate constituents. Establish small disjoint groups (cells) to follow through on the common purpose. Create a loose communication network between cells and employ open but encoded communications.
Examples	• Al Qaeda(Gryc, 2005) • Cyber-hacker organizations (such as the Chaos Computer Club, http://www.ccc.de)

Summary

We started with a self-organizing foundation based on six necessary characteristics: whole–part relationship, conditional dependency, common purpose, autonomy, situational awareness, and adaptability. We related these self-organizing characteristics to those exhibited by any SoS. While any SoS has some of these characteristics, they are not sufficient on their own to support self-organization.

The two SoS examples we discussed employ distinct patterns of self-organization. Ushahidi is an example of crowdsourced incident reporting, supporting security with open communications for situational awareness. Al Qaeda, conversely, is an example of clear-cause coordination, supporting security with no communications to eliminate vulnerability.

The self-organizing characteristics support a system engineering approach to recognizing and planning for self-organization in SoS design. The characteristics and related patterns add to the body of systems engineering knowledge on self-organization and provide tools that systems engineers can use in evolutionary SoS design. Systems engineering would do well to exploit self-organizing SoS patterns to address the challenges of contemporary security threats.

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