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Architecting of Systems of Systems for Delivery of Sustainable Value

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Abstract

Requirements need be established for architecting systems of systems (SoS) for sustainable delivery of value to users. This paper sketches a general methodology to establish such requirements. The methodology involves a system architecture paradigm, a sustainability analysis, a similarity principle, and a derivation of design requirements. The methodology is described in concrete terms as it is applied to an ad hoc SoS sensor network, which is required to provide sustainable delivery of information for use within a missile defense context. Bounds are then established on the network connectivity and interoperability measures. This work demonstrates a methodology to enable designing requirements for architecting a system of systems for sustainable delivery of value.

Key words: Systems of systems, system of systems architecting, sustainability, similarity principle, entropy, requirements.

1. Introduction

A research area of interest is to gain insights into architecting a system of systems (SoS) for sustainable performance. By sustainable performance it is meant sustainable delivery of value to users of the SoS. A SoS is a composite system that is comprised of component systems, each of which serves organizational and human purposes and may be locally managed and optimized independently, or nearly so [1]. The component systems tend to be large-scale and complex. A large-scale, complex system consists of a large number of elements that interact with each other; complexity is related to the real-time, unplanned, evolving large size of a system. Not only does the complexity of a system induce vulnerability of the system [2], but lacking interoperability

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among the elements that make up the system also degrades the performance of the system [3]. A SoS can be designed top-down or formed by combining existing systems into a new larger system to achieve some new operational capability. The work in this paper focuses on designing a SoS top-down.

Huynh et al. [4] sketch a methodology for architecting a system for sustainable delivery of value. This paper focuses on the extension of the methodology to architecting a SoS. A similarity principle (to be discussed later) plays a key role in the extension.

To discuss the methodology in concrete terms, a missile defense (MD) SoS is formed by combining or gluing a number of independent MD systems. A MD system, in its most simplistic yet fundamental form (Fig. 1), is assumed to have three main components − BMC2 (battle management, control and command), a sensor network, and shooters (interceptor launchers). The shooters need a fire solution (i.e., an intercept solution) in order to effect an intercept of a target (incoming missile). The BMC2 receives and combines the target state estimates from the participating sensors to derive an intercept solution. The target state can include the type of the target (missile), its position and uncertainty (associated error), its velocity and uncertainty. Note that only the system BMC2 can order its shooters to engage a target.

Figure 1 – Missile defense system context diagram.

A general question is: How are requirements established for architecting a SoS that continues to deliver desirable value to its users in the face of adversity caused by environmental or mission changes? A specific question is: How are requirements established for architecting a MD SoS network consisting of the sensor networks organic to the component MD systems for sustainable delivery of desired value to the MD SoS BMC2 as well as to the component MD system BMC2s?

The SoS needs and its functions are assumed to have been identified. The approach to answering the specific question immediately above involves subscribing to the systems architecting paradigm [5], modeling network complexity and interoperability [3, 6], performing a sustainability analysis [7], invoking a similarity principle [8, 9], and deriving the MD SoS network architecting requirements.

As pointed out in [3, 6], analysis of the performance of such a sensor network is often based on the assumption that connectivity and interoperability among the sensors are perfect. By connectivity it is meant the sensors can discover and communicate with each other; by interoperability it meant there is no semantic or syntactical problem that would prevent successful combining of the sensor data. In reality, sensors do drop out of the network as a result of malfunction or hostile acts, and interoperability might not exist or can degrade for some reason. In the presence of external factors (environment dynamics) that might affect these two measures ─ connectivity and interoperability, the issue of network sustainability arises. A sustainable network is one which is resilient and adaptive to the dynamics of the environment. Network sustainability is necessary for sustained delivery of distributed fusion performance of the sensor network. Network sustainability necessitates a sensor network architecture that maintains such sustained delivery. As will be seen later, for the sole purpose of illustration, interoperability measure will be assumed to be fixed, and requirements on connectivity measure are to be determined.

The methodology to establish requirements for designing a sustainable architecture is described in concrete terms as it is applied to an *ad hoc* SoS sensor network, which is required to provide sustainable delivery of sensor fusion performance beneficial (value) to the BMC2 components of the missile defense SoS. Specifically, the system architecting paradigm espoused in [5] is adopted, a concept and a form for SoS sensor network are defined, the results of the sustainability analysis in [7] are used, and the similarity principle enunciated in [9] is adapted to deriving the desired requirements. Bounds are established on the ability of elements of the networks to discover and to communicate with each other and the ability of the elements to interoperate with each other. This work will thus demonstrate a methodology to enable the development of requirements for architecting a SoS for sustainable delivery of value.

The goals of this paper are:

- Apply the architecting paradigm espoused in [5] to SoS architecting.
- Capture the models of network connectivity and interoperability [3, 6] and the results of the sustainability analysis of *ad hoc* wireless sensor networks using the sustainability index [7].
- Apply the similarity principle [9] and combine the results of the sustainability analysis of *ad hoc* sensor networks and the architecting paradigm to provide an illustration of the methodology for SoS architecting for sustainable performance.
- Illustrate the methodology with an *ad hoc* wireless MD SoS sensor network for distributed sensor fusion.

The rest of the paper is organized as follows. The architecting paradigm espoused in [5] is discussed. The binary hypothesis distributed fusion problem and the models of network connectivity and interoperability described in [3, 6] are then briefly explained. The results of the sustainability analysis of *ad hoc* wireless sensor networks using the sustainability index [7] are then summarized. A similarity principle applied to architecting a SoS is enunciated by adapting the similarity principle in [9] to SoS architecting. The requirements on the interoperability and connectivity measures are then derived. Finally, the paper ends with some closing remarks.

2. Systems Architecting

Crawley and Simmons [5] formulate a preliminary system architecting paradigm, in which, as shown in Fig. 2, architecting a system starts with function which is mapped to form by concept. Architecture is “the embodiment of concept and the allocation of physical/informational function to elements of form, and definition of interfaces among the elements and with the surrounding context” [5]. The definition of architecture can be captured as a quadruplet: (Function, Concept, Form, Interfaces; Context). Refer to [4] for a detailed elucidation of the application of this system paradigm to architecting a MD system.

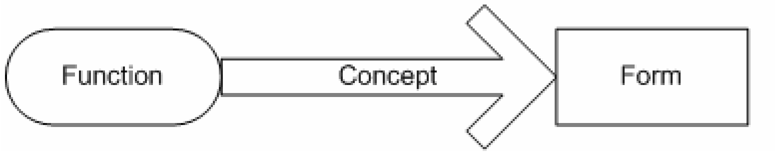

Figure 2. Concept maps function to form

In this paper, a function of the MD SoS is to detect and track an incoming missile. A concept in this case is ‘object state estimation with a distributed fusion sensor network to be used by all BMC2 components to determine intercept solutions (fire control solutions).’ An ad hoc MD SoS sensor network is a form to deliver estimates of the target state to the MD system BMC2 components. It results from combining distributed fusion sensor networks associated with (organic to) the component MD systems, enclosed by the large oval shape in Fig. 3.

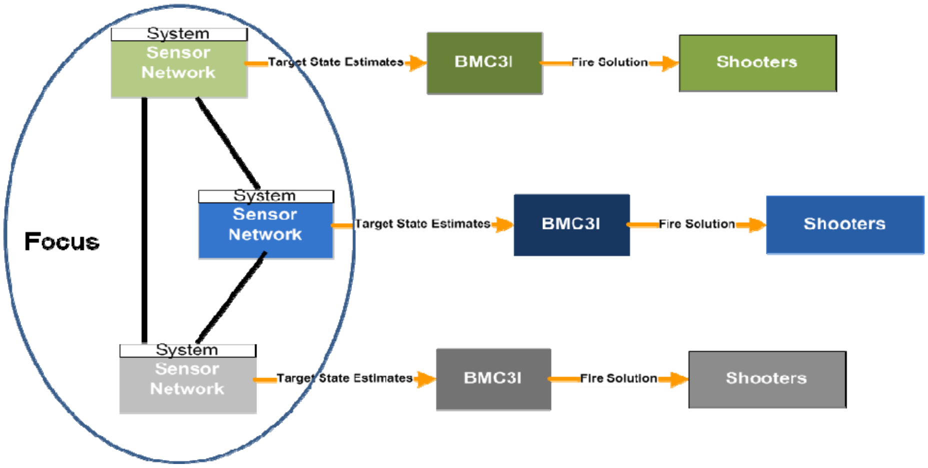

Figure 3. SoS sensor nework concept

In term of relationships, the connections among the elements of this ad hoc MD SoS sensor network are assumed to be wireless. ‘Fire control solutions for missile engagement’ is the context in which the sensors organic to the MD systems are networked (to provide the target state estimates). As distributed fusion of sensor observations of the incoming missile to provide accurate estimates of the target state benefits the component MD system BMC2s in formulating fire control solutions, value is delivered to the BMC2s. The more accurate is the target state, the more it is of value to the fire control solution. The value that need be sustained is the target state. If the estimated target state remains accurate, then the value is sustainable. The required sensor network architecture attributes corresponding to the architecting paradigm is shown in Fig. 5 [4].

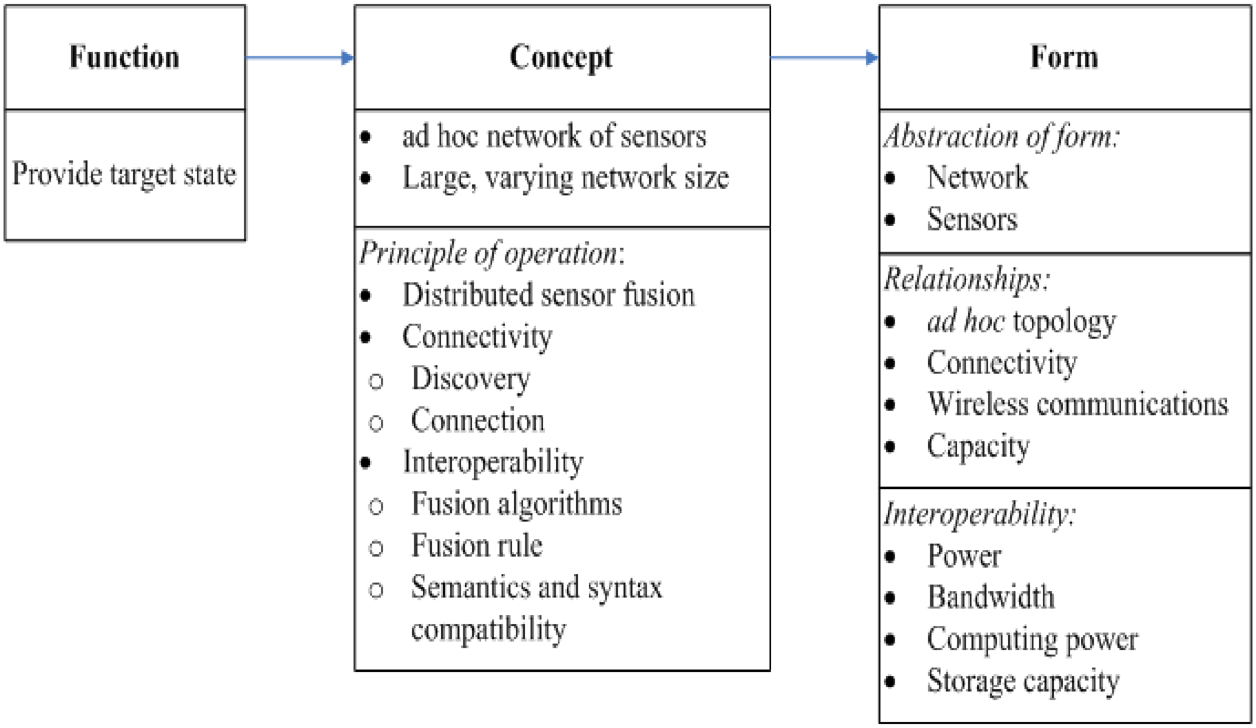

Figure 5. Required sensor network architecture attributes

3. Distributed Sensor Fusion Problem

The focus of this paper is on systems architecting, not on sensor fusion per se. For illustration purposes, the binary hypothesis distributed fusion problem is considered here, just as in [3, 6]. The binary hypothesis distributed fusion problem is one in which sensors in a network of N sensors that observe a common phenomenon (e.g., a space object, a threat, etc.) pass their observations (measurements) among themselves, and independently process all the observations to produce a binary output ─ either the phenomenon is present or absent. For simplicity, the component MD sensor networks all have the same number of sensors, N, the local decision rules are assumed to be identical, and all sensors are assumed to have the same probability of detection, P_D, and the same probability of false-alarm, P_F. Let $C_F$denote the cost of making a false-alarm decision and C_D the cost of making a correct decision. In this work, the K-out-of-N fusion rule is used, for which the optimal value of K , K_{opt} , is given by [10]

$$K_{opt} = \begin{cases} \lceil K^* \rceil, & \text{if } K^* \geq 0 \\ 0, & \text{otherwise'} \end{cases}$$

where $\lceil . \rceil$ denotes the standard ceiling function, and

$$K^* = \frac{ln\left[\frac{C_F}{C_D}\left(\frac{1-p_F}{1-p_D}\right)^N\right]}{ln\left[\frac{p_D(1-p_F)}{p_F(1-p_D)}\right]}.$$

4. Representation of Network Complexity & Interoperability

Each component MD sensor network is assumed to be an *ad hoc* network of N sensors. Two sensors in the network are connected if they discover each other — assumed with a constant probability p_d — and, upon discovery, the communication channel between them is established — with a variable probability p_κ. Then the probability p_c that a pair of sensors is connected is $p_c = p_\kappa p_d$, which, by virtue of p_κ, is not constant. The degree of a sensor [11, 12] follows a binomial distribution with parameters p_c and $N - 1$. The probability of degree l, $P(l)$, is then

$$P(l) = \binom{N-1}{l} {p_c}^{l}(1 - p_c)^{N-1-l}.$$

As in [13], $\chi_o$denotes the complexity of a network, defined as the mean number of links supported by a sensor of the network; that is, $\chi_o = \sum_{l=0}^{N-1} lP(l)$. χ_o is thus the connectivity measure of the network. Then a simple computation leads to

$$\chi_o = p_c(N-1) \text{ or } \chi_o = p_c p_\kappa(N-1).$$

The more complex the network is, the higher is the value of χ_o. The *ad hoc* sensor network is thus modeled as a random network [11].

Let p_s be the probability (assumed constant) that a sensor is interoperable with other sensors. As explained in [3, 6], the probability that k sensors are interoperable is given by

$$P(k) = \binom{N}{k} {p_s}^{k}(1 - p_s)^{N-1-k}.$$

The interoperability of the network, denoted by χ_1, is defined as $\chi_1 = \sum_{k=0}^{N} kP(k)$. A simple computation then leads to $\chi_1 = p_s(N - 1)$. χ_1 is thus the mean number of interoperable sensors. If N is known, any property which can be expressed in terms of p_c and p_s can also be expressed in terms of χ_o and χ_1.

A sensor is in state 1 if its degree is at least equal to 1 and if it is interoperable with other sensors. The number of sensors in state 1, denoted by X_1 , takes the values of $0,1,2, \dots, N$. The average number of interoperable nodes K is then

$$\bar{K} = E(X_1) = \left[1 - \left(1 - \frac{\chi_o}{N-1}\right)^{N}\right]\frac{N\chi_1}{N-1}.$$

In the $N \to \infty$ limit, $\bar{K} = E(X_1) = (1 - e^{-\chi_o})\chi_1$. Given the size of the network and the probability of discovery and the probability of communication between two sensors, the complexity and interoperability of the network can be determined. The mean number of the sensors in state 1 can then be readily obtained.

5. Sustainability Analysis

Sustainability of a sensor network depends on the resilience of the network in the face of the dynamics of the environment. Assessing the sustainability of an *ad hoc* sensor network means determining impacts of the network complexity and interoperability on the distributed sensor fusion performance of the *ad hoc* sensor network in the presence of forces of change [7]. In [7] the *ad hoc* sensor network is treated as an ecosystem with its complexity and interoperability implicitly built-in. The sustainability of the *ad hoc* network is then assessed; that is, the critical connectivity for which the network fails to perform according to a fusion rule is determined. The sustainability analysis uses the so-called sustainability index [14], a quantitative measure used in ecologically conscious process systems engineering [15]. Derived in [7] for the *ad hoc* network, the sustainability index is give by

$$SI = \frac{(1-e^{-\chi_0})\chi_1}{K^*}.$$

For the network to be able to sustain its performance, it is required that $SI \geq 1$, which, as derived in [4], leads to the requirement that each sensor network organic to a SoS member system is sustainable if

$$\chi_1 \geq \frac{K^*}{1-e^{-\chi_0}}.$$

Each sensor network organic to a SoS member system is thus in two possible states:

State 1: if $\chi_1 \geq \frac{K^*}{1-e^{-\chi_0}}$
Sate 0: Otherwise

Note that these states refer to the states of a MD sensor network and that the states defined in Section 4 refer to the states of a sensor. Each MD sensor network is thus a binary element of the MD SoS sensor network.

6. Similarity Principle

In [9] Lin enunciates the Similarity Principle for a mixture of chemical species:

> "*If all the other conditions remain constant, the higher the similarity among the components is, the higher value of entropy of the mixture (for fluid phases) or the assemblage (for a static structure or a system of condensed phases) or any other structure (such as chemical bond or quantum states in quantum mechanics) will be, the more stable the mixture or the assemblage will be, and the more spontaneous the process leading to such a mixture or an assemblage or a chemical bond will be.*"

A MD SoS can be viewed as mixture of the MD component systems. Adopting the similarity principle espoused by Lin [9], a similarity principle for a SoS architecture can be enunciated as follows:

> "*The higher the similarity among the systems of a SoS is, the higher the value of the entropy of the SoS will be, the more stable (or sustainable) the SoS will be.*"

The state of maximal entropy is the state of maximal similarity (or indistinguishability) [9]. Similarity in architecting a SoS sensor network has to do with the similar ability of each MD system sensor network to provide target estimate of value to the MBC2 components. Following Lin [8], a similarity index, Z, is defined according to $Z = \frac{S}{S_{max}}$, where the entropy of the SoS is

$$S = -\sum_{j=1}^{\aleph}\sum_{i=}^{M} p_{ij} \ln p_{ij}$$

in which $\aleph$ is the number of sensor networks, M is the states of the network, and p_{ij} is the probability that the j^{th} sensor network is in state i, and $\sum_{j=0}^{M} p_{ij} = 1$. For the MD SoS at hand, $\aleph$ = 3 and M = 2. $S_{max} = \ln W$, where W is the number of possible states of the SoS sensor network.

The similarity index is then given by

$$Z = -\frac{1}{S_{max}} \sum_{j=1}^{\aleph} \sum_{i=}^{M} p_{ij} \ln p_{ij}.$$

The derivation of the requirements follows.

7. Derivation of Requirements

It follows that $Z = -\frac{1}{S_{max}} \sum_{j=1}^{3} \left(p_{0j} \ln p_{0j} + p_{1j} \ln p_{1j}\right)$, where $p_{0j}$is the probability that the j^{th} nework is in state 0 and $p_{1j}$is the probability that the j^{th} nework is in state 1. Now, Z is maximum if $\frac{\partial \sum_{j=1}^{3} (p_{0j} \ln p_{0j} + p_{1j} \ln p_{1j})}{\partial p_{1j'}} = \sum_{j=1}^{3} \frac{\partial}{\partial p_{1j'}} \left(p_{0j} \ln p_{0j} + p_{1j} \ln p_{1j}\right)$, which then yields $p_{1j} = \frac{1}{2}$ for $j = 1,2,3$. In this case, $Z_{max} = 1$.

It follows then that $Pr\left(\left(\chi_1 \geq \frac{K^*}{1-e^{-\chi_0}}\right)\right) = \frac{1}{2}$ or $Pr\left(\left(\chi_1 (1 - e^{-\chi_0}) \geq K^*\right)\right) = \frac{1}{2}$. The similarity index Z is maximum when, for each MD system sensor network, with the results from Section 4 incorporated,

$$Pr\left(\left(p_s (N-1)\left(1 - e^{-p_c (N-1)}\right) \geq K^*\right)\right) = \frac{1}{2}.$$

In the case of large N,

$$Pr\left(p_c \geq -\frac{\ln\left(1 - \frac{K^*}{p_s N}\right)}{N}\right) = \frac{1}{2}.$$

Thus, as the network size N can change in real time, for the *ad hoc* MD sensor network to be able to sustain its delivery of value to the BMC2 component of the MD system, it is then required that, for each sensor in the SoS network or network architecture,

$$p_s = \frac{K^*}{N\left(1 - e^{-NF^{-1}\left(\frac{1}{2}\right)}\right)}$$

where p_s is given and p_c is treated as a random variable with a cdf F.

8. Conclusion

This paper discusses a general methodology to derive requirements on architecting a SoS to provide sustainable delivery of value. The methodology involves the system architecture paradigm espoused in [5], modeling of network complexity and interoperability [3, 6], sustainability analysis such as the analysis discussed in [7], the similarity principle [8, 9], and the derivation of the requirements. The methodology is described in concrete terms as it is applied to binary hypothesis distributed sensor fusion in an *ad hoc SoS* sensor network, which is required to provide sustainable delivery information for use within the context of a missile defense system. A simple fusion rule is employed. Constraints are then established on the network connectivity and interoperability measures. This work demonstrates a methodology to enable defining requirements for architecting a SoS sensor network for sustainable delivery of value. The methodology can also be employed to derive requirements on the other MD system components such as the MD BMC2 element.

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