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An Army-Centric System of Systems Analysis (SoSA) Definition

by Jeffrey A. Smith, Jayashree Harikumar, and Brian G. Ruth

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An Army-Centric System of Systems Analysis (SoSA) Definition

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14. ABSTRACT
Over the course of the last several years there has been much discussion of a concept called the "system of systems" (SoS), and many proposed definitions that capture features of various SoS. These numerous definitions offer the means to identify SoS; yet, from an analytical point of view, we feel they do not offer the clarity required to construct a well grounded framework to analyze these SoS. Over the course of our research to develop such a framework, we realized that there is another perspective from which to view the notion of a SoS. This perspective, rooted in the analysis of a military SoS, explicitly recognizes three existential concepts present in any military SoS that are also likely present in non-military SoS. The purpose of this report is to highlight these concepts, and relate them to the base of established literature regarding SoS.

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Contents

List of Figures **iv**

1. Introduction **1**

2. Principal Characteristics for System of Systems Definition **2**

3. A Novel Perspective on SoS **3**

3.1 Nested Concepts and Inter-Related Purposes....4

3.2 Dynamic and Evolving Processes....5

3.2.1 State/Phase Space and World Lines....7

3.2.2 Homeostasis and Homeodynamics....14

3.3 Sociotechnical Systems Theory....21

3.3.1 Multiscale Analysis of Complex Systems....24

4. A Concept of SoS Analysis **26**

5. Conclusions **26**

6. References **28**

List of Symbols, Abbreviations, and Acronyms **31**

Distribution List **32**

List of Figures

Figure 1. Phase space for a notional flying insect. 9

Figure 2. Dynamic response for the notional flying insect within an operational context. (a) Notional time series data presenting insect displacement as a function of sampling time. (b) The same dataset displaying displacement at time *t* versus displacement at time $t + \Delta t$...11

Figure 3. World line, world sheet, and world volume associated with the time-evolved states of an object with different degrees of positional uncertainty. 13

Figure 4. Homeostatic process within a complex adaptive system. 16

Figure 5. Homeodynamic process within a complex adaptive system. 19

Figure 6. Range of homeodynamic efficiency (RHE) for a general organizational SoS.............21

Figure 7. The NATO C2 conceptual model...24

1. Introduction

Over the course of the last several years, there has been much discussion of a concept called the "system of systems" (SoS), and many proposed definitions that capture features of various SoS. These numerous definitions offer the means to identify systems of systems; yet, from an analytical point of view, we feel they do not offer the clarity required to construct a well grounded framework to analyze these SoS. We believe that there is another perspective from which we can view the notion of a SoS. This perspective is rooted in the analysis of a military SoS. We hypothesize that there exists three basic concepts in both military SoS and non-military SoS. These concepts are (1) nested concepts and inter-related purposes, (2) a notion of dynamical processes, and (3) identification of sociotechnical concepts in all SoS. The purpose of this paper is to highlight these concepts, and relate them to the base of established literature regarding SoS.

Information is recognized as power. Technology is used to gather and disseminate information in the U.S. Army. We need to assess the technology and information gathered for army personnel. In addition, we cannot assess what technology can give us if we do not have a good understanding of the system(s) in which the technology will be used. Specifically we need to do a SoS analysis (SoSA). To do analysis we want to develop an analysis methodology. Issues that confront us before we can develop an analysis methodology are:

1. Multiple definitions of SoS.
2. What behavior or property of a system characterizes it as a SoS?
3. Multiple sensors (technology) gather information. How do they work together? Do they interfere with each other?
4. Do SoS differ with specific Commander's intent?
5. Emerging behavior from systems (sensors and personnel) that operate in differing scenarios.
6. Interaction of the emergent behavior of the systems in a SoS.
7. Impact of collaborative technologies in a SoS.

In the following sections, we discuss the principal characteristics for SoS definitions, as found in literature, and the three existential concepts we believe is present in both military and non-military SoS. We introduce these three existential concepts to highlight that SoS has special characteristics that limit the potentiality of multi-methodologies, especially in the model formulation and system design phases (*1*). We hypothesize that for SoS analysis, two basic model types are needed: (1) a model to abstract the basic structure and behavior of SoS, and

(2) a model to combine the data with simulation for guiding decisions (*2*). The proposed concept of SoSA is that if one accepts the above model formulation then it implies that the output of a SoS model will be probabilities of possibilities.

2. Principal Characteristics for System of Systems Definition

Literature review (*3*, *4*) provides many definitions for SoS. A common thread among these definitions is five principal characteristics that most authors think a SoS should possess. These characteristics were first identified by Maier (*5*, *6*) and in this section we will address these five principal characteristics; and the relevance and associated debate over the interpretation of these characteristics.

1. Operational Independence of the elements: This principal requires the component systems in a SoS to be independently operational. A SoS is built to fulfill specific purpose(s). In such a system the normal operational mode of the component systems can be subordinated to the central (desired) operational mode of the system. Alternately, when component systems are more collaborative (less directed) the central operational mode of the system may be compromised.

2. Managerial Independence of the elements: In addition to being independently operational, this principal states that component systems may be acquired and operated independently and can maintain an operational existence independent to the SoS. In addition to the constraints imposed by principal 1, evolution of the component systems places constraints on acquisition and operation of the component systems and in turn the management and operation of the SoS.

3. Evolutionary Development: The SoS is composed of systems that are bought together to satisfy a higher task/purpose. The existence of SoS can be evolutionary as tasks and purposes are added, removed or modified with usage. This principal states that a SoS does not appear fully formed. This implies that as the SoS evolves it is likely that the overall system 'value' is no longer approximately equal to the sum of the component system 'value.' The SoS could now provide a greater functionality than its component systems or the interactions between the component systems could reduce the combined capability of the overall system. A system value is determined from the desired system attributes. However as the overall system evolves the component system attributes that combine to generate the SoS utility impact SoS costs.

4. Emergent Behavior: The behavior of a SoS is not the behavior of any one component system. The collective behavior of the interacting systems in a SoS defines the behavior of the SoS. The principal purposes of the SoS are fulfilled by these system behaviors. However, when component system attributes interact to produce the desired emergent

attribute of the overall system, it is possible that some undesired emergent behavior be observed. This impacts system cost, design and 'knowledge' of the system.

5. Geographic Distribution: The geographic extent of the component systems can be large. The only constraint on the geographic extent is that the components can readily exchange information but not mass nor energy. Component systems adapt to changing environment and when systems are geographically distributed there is no common thread to predict the emergent system behavior. In addition, for a military SoS the geological extent of the deployed SoS is defined by purpose, available materiel and soldier skills vice the other way around.

In a review of literature (*7*), most authors agree on the five principal characteristics, explicitly defined by Maier, for describing SoS. A military SoS also exhibits many of the Maier defined characteristics either by design consequence or interaction with its environs. A network enabled military SoS is driven by purpose. It has to continuously evolve in order to survive and fulfill its mission. At the same time, each system in a military SoS has to maintain its operational and managerial independence in order to fulfill its sub tasks and the overall system mission. One observes a continuous tradeoff between independent and interdependent behavior in a military SoS brought about by conventional force-on-force type of engagement and effects based asymmetric (different complexity at different scale) warfare.

A military system is not just about its purpose but also about its structure and how it has been put together by whom and why. Military systems evolve and the change occurs at both the component system level and the SoS level. System scalability is affected when a system change occurs. A change in system scalability impacts system cost. A SoS put together for a certain purpose *may* be scalable to handle extra work but the initial overhead and the cost to maintain the updated system has to be considered. System scalability factors, such as number and type of component systems, play an important role when a system is not used for the scale it has been modeled to. In addition, a military system (SoS) may be *perfect* for a certain scenario but relatively useless in another scenario. No system can be diverse enough to respond to every changing uncertainty and only the known specifics of the problem can define the SoS and the constraints in which the system can be used. Adaptation of a military system to its purpose, available materiel and Soldier skill is critical, and this implies that scalability is also a *sufficient and necessary* defining characteristic of a military SoS.

3. A Novel Perspective on SoS

In the military domain, the SoS concept has been useful in describing the complexity of the network enabled/connected battlefield operating systems. The Department of the Army (*8*) relies on the SoS concept for the Future Combat System (FCS) strategy (*9*). However, these numerous definitions, from an analytical point of view, do not offer the clarity required to construct a well grounded framework with which to analyze these SoS. Bjelkemyr et al. (*10*) pose questions for SoSA. They suggest that the SoS elements must first be clearly understood in addition to the links that tie the component systems together. Analysts attempting to develop metrics to address SoSA must address three components: (1) what are the drivers for transformation in the SoS? (2) is there a measure to describe the state of well being in the SoS? and (3) how can this state of well being be assessed in the SoS?

In this section, we offer a novel perspective from which to view the SoS. We believe that the SoS lexicon as defined in literature (*2*, *5*, *6*, *11*, *12*) does not apply (is not complete) in the military domain. In a military domain there are interrelationships and consequent emerging behaviors between the systems in a SoS. Consequently, analysis of a SoS in a military domain needs to account for the ever changing and evolving systems that define the SoS. In addition, we believe that the mission drives the SoS and therefore a generalized treatment of the emergence and evolution for all types of SoS is not possible. In a military SoS, emphasis is given to decision makers and assets because as stated by Dahmann (*13*), decision making and its consequences are central to the function of the military SoS.

Based on literature search and discussions therein, we believe in order to develop an analytical framework with which to analyze a military SoS, we need to recognize the three existential concepts present in any military SoS. The concepts are (1) nested concepts and inter-related purposes, (2) dynamic behavior and evolving processes, and (3) sociotechnical system concepts.

3.1 Nested Concepts and Inter-Related Purposes

The military SoS does not exist in vacuum. It has a mission to perform that is unique to that time, place, and the collective involved. The mission or purpose drives the functioning of the military SoS. Purpose gives the warfighter a reason to perform his task(s). The commander communicates his mental image of the purpose, decomposed in time, to his subordinates and peers via inter-related and nested concepts. An important concept to remember is that nested concepts do not control but just constrain the subordinate commander's action (*14*), in order to maintain a unity of effort.

In order to make decisions, a commander uses both the current situational context and a mental image of the situation projected into the future. A commander then needs to communicate this mental image to the subordinates so that they can focus their efforts/actions to a shared common goal. A commander's vision includes the subordinates' requirements and responsibilities while providing the purpose, and the desired end state for that military unit. In current Army doctrine, commander's intent is acknowledged as the most important part of an operations order. A nested concept is the vehicle to communicate this mental image throughout the organization. It defines the commander's relationship with superiors, peers, and subordinates. FM 3-0 (*15*) and other literature (*16–20*) defines nested concepts as a "concept whereby each succeeding echelon's concept is nested in the other." At each level of command, commanders provide intents and concepts to unite their subordinates and peers in a coordinated effort to successfully complete a mission. By nesting concepts and thus purposes for subordinates the commander achieves unity of effort in the unit. As the subordinate units within the force get smaller and more spatially dispersed, this shared mental image grows in importance and remains essential to maintain unity of effort and a cohesive organization. Neither nested concepts nor inter-related purposes tell the warfighter how to get from the current state to the desired end state. The concept of operations provides this "bridge of action" to subordinates.

The concept of operations is a statement that directs the manner in which subordinate units cooperate to accomplish the mission and establishes the sequence of actions the force will use to achieve the end state. It defines tasks as assigned to specific units, and the interdependence of the former as executed by the latter. The value of concept of operations is that it establishes the subordinate's relationships with the commander's unifying image and informs them of their responsibility to attain the common goal.

Ackoff and Emery (*18*) characterize human systems as purposeful systems whose members are also purposeful individuals that intentionally and collectively formulate objectives and are component parts of larger purposeful systems. In a military SoS, the above characterization of a purposeful system implies that we can consider the commander and the subordinates a purposeful system. For Ackoff and Emery (*18*), a purposeful system or individual is ideal-seeking if it intentionally chooses another objective that more closely approximates its ideal. An ideal-seeking system or individual is necessarily one that is purposeful, but not all purposeful entities seek ideals. The capability of seeking ideals may well be a characteristic that distinguishes humans from anything that they can make, including computers.

SoS are created with the intention that its emergent behavior realizes an intended mission; thus, they become more than the sum of its parts. Yet, when they are improperly taken apart for analysis, they lose this important property. In an *analytical* approach (to study any problem), explanation of the whole is deduced from the explanation of the parts. In contrast, one could use the synthetic approach where a part's functionality is explained in terms of its role in the larger system. For military SoS, we suggest the use of nested concepts and inter-related purposes, in conjunction with a commander's intent and concept of operation to decompose the SoS for analysis, and then properly integrate the results into a holistic analysis of the SoS.

3.2 Dynamic and Evolving Processes

The notion of dynamic processes is a critical contributing element when considering what makes up a military SoS. The dynamic interplay between complementary mission-supporting purposes as SoS component systems operationally respond to uncertainty and change (both internal and external) ultimately determines success or failure in achieving the intended mission objective. Tracking the evolving SoS trajectory through an associated operational state space (as a function of time) serves to illustrate this purpose-driven dynamic. But the question remains: how do we characterize this type of dynamic process in order to analyze it?

To properly answer this question, we need to identify the common characteristics among the decision-making processes (DMP) that manifest across a variety of SoS examples. These characteristics include the following (*20*).

- The utility function of the decision maker utilizing a SoS DMP may be difficult to quantify.
- The relative utility of a specific decision option to each component system within the SoS may greatly vary.
- The utility function for a SoS (or SoS subunit) course of action (COA) may be a nonlinear composite of utility functions from individual constituent systems.
- The SoS COA utility function is generally context sensitive. As the environmental context evolves over time, so too does utility function associated with that COA.

These common characteristics imply both a natural time component of SoS decision-making and also a natural uncertainty associated with the information under which decisions are made. Regarding the latter, we can logically ascertain the following assumptions.

- Decisions are made with the information available to the decision maker at the time of the decision.
- The quality of the decision is only known after the realization. A correct decision could result in an undesired outcome but it is still the best decision.

From these observations, we can conclude that the inherent complexity within SoS DMPs tends to render mission outcome prediction based solely on existing *a priori* knowledge of a situation very challenging (if not often impossible).

When collectively examined, the common characteristics of SoS-related DMPs cited in the previous paragraph tend to suggest several different perspectives from which to analyze SoS dynamic processes. The first of these perspectives is the concept of *synchronous behaviors*, which are characteristics, shared among different SoS variants that range from physical, biological, to social systems. These behavioral types include the processes of how people reach consensus in group interactions and decision making, as well as collective behaviors that exhibit data cluster-of-clusters type of phenomena. Coordinated synchronous behaviors demonstrated within a SoS require the pre-existence of a durable communication network connecting the various constituent component systems making up the SoS.

A second perspective from which to analyze dynamic processes within a SoS are the complementary concepts of non-stationary and non-ergodic behaviors. A discrete time series $x(t_1)$, $x(t_2)$, $x(t_3)$, … (where $x(t_i)$ is the scalar or vector state of quantity x measured/sampled at the i^{th} time step t_i) is *non-stationary* if, for some m, the joint probability distribution of $x(t_i)$, $x(t_{i+1})$, $x(t_{i+2})$, …, $x(t_{i+m-1})$ is dependent upon the value of t_i (*21*). Similarly, a discrete time series

$x(t_1)$, $x(t_2)$, $x(t_3)$, … represents a *non-ergodic* process if $\bar{x}(t_i)$, the time-averaged value of the process, where

$$\bar{x}(t_i) = \lim_{N\to\infty} \frac{\sum_{i=1}^{N} x(t_i)}{N}$$

is **<u>not</u>** equal to $\langle x(t_i)\rangle$, the ensemble average of $x(t_i)$ (i.e., the value of x sampled at the same time t_i over the ensemble of all possible realizations of the process), where

$$\langle x(t_i)\rangle = \lim_{M\to\infty} \frac{\sum_{j=1}^{M} [x(t_i)]_j}{M}$$

and $[x(t_i)]_j$ is the j^{th} realization of $x(t_i)$. Thus, non-ergodic processes usually reflect dynamical systems far from an equilibrium state (*22*). A SoS will often exhibit non-stationary and non-ergodic behavior in large time due to nonlinearity of the composite collective system.

A third analytic perspective from which to address dynamic processes is the notion of *multiple time scales*. SoS often exhibit important behaviors that are demonstrated over multiple time scales, including

- a *fast* time scale,
- a *slow* time scale, and
- a *large* time scale.

These differentiated time scales generally scale proportionally with various spatial scales within the SoS.

- *Fine-grained/microscale* functions evolve according to a fast time scale.
- *Coarser-grained/mesoscale* functions evolve at a slower time scale.
- Finally, *collective/macroscale* functions evolve according to a large time scale characteristic of the SoS as a composite whole.

By integrating the concepts of synchronous, non-stationary, and non-ergodic behaviors and multiple time scales into a single analytic meta-concept with multiple perspectives, the SoS analyst is provided with an insightful "lens" for the study of collective dynamic and evolving processes exhibited by a military SoS.

3.2.1 State/Phase Space and World Lines

In the previous section of this report, we discussed the dynamical processes that tend to operationally manifest within military purpose-driven SoS. Generally, these processes can be quantitatively captured and recorded as time-evolving metrics that, over time, generate trajectories within an associated operational state space. We can thus characterize and analyze the emergent behavior generated by a SoS by examining these related state space histories (representing the dynamical evolution of a SoS collectively or of individual component systems as a function of time). In this section, we introduce the necessary foundational concepts that provide a means to realize SoS state space based analysis.

We start out with the most basic concept of all: the *phase space*, which is a multi-dimensional coordinate system whose axes represent the measurable variables of a particular system. For a dynamical system, the phase space must be capable of representing all possible states that the system might occupy as a function of time, where each possible state of the system corresponds to one unique point in the phase space. Generally, a phase space is finite-dimensional, consisting of an infinite number of points forming a smooth manifold. The phase space axes – where each axis reflects a specific degree of freedom (i.e., physical, functional, cognitive, operational) – must span the configuration state space of the system under analysis. An instantaneous state of the system is thus represented in phase space by a point.

Figure 1 illustrates an example of a simple phase space formed by the time-dependent variables displacement (from a reference location) $d(t)$, velocity $v(t)$, and acceleration $a(t)$ describing the motion of a notional insect with the capability of flight (e.g., a common house-fly), where t is the time at which the variables were sampled. When plotting a set of system variables in phase space, there is an underlying assumption that the variables are all sampled at the same rate. If they are not, it is difficult to make an interpretation. In order to properly record a set of system variables within the respective phase space, one must think of the variables sampled at each time step as the coordinates for a point in the space. For the example displayed in figure 1, this sampling process produces a set of discrete points scattered across a small region of the phase space (indicating the abruptly-shifting flight of a flying insect). These points describe the *phase space trajectory*: the path through a phase space traced by a dynamical system as a function of time; measured as a time-ordered sequence of system states. As the system evolves over time, a succession of such states is produced, giving rise to the phase space trajectory that serves to graphically capture the time evolution of the system. For purposes of informative visualization, the trajectory points displayed in figure 1 are shown to fade as a function of increasing age (thus conveying an implied graphical description of the flying insect as a function of increasing time), where a forced perspective depicts larger data points as being closer to the viewer. Here, the phase space trajectory portrays the insect as initially staying close to the $d(t) = 0$ reference location, then flying out with increased velocity and acceleration later in time.

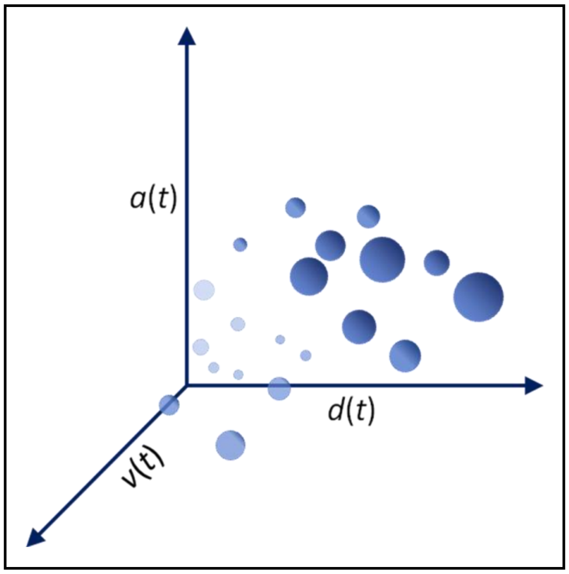

Figure 1. Phase space for a notional flying insect.

Once we have established the concept of a phase space for graphically conveying the time history of the state of a dynamical system (or sub-state for high-dimensional systems such as SoS), we can next extend the formalism by providing one (or more) means to identify phase space patterns indicating emergent behavior on the part of the system. One such means is the concept of a phase space *attractor*: a set of states (i.e., points within a phase space) towards which a dynamical system evolves (regardless of initial conditions) as a function of time. In a dissipative dynamical system, as time progresses, the phase space trajectory will tend towards a mathematical limit. We call this mathematical limit the "attractor:" an equilibrium location in the system phase space that describes a time-independent (i.e., stationary) situation. This yields a phase space point (or point cluster) towards which all possible system histories tend to converge.

From a practical point of view, the observation of a real dynamical process demonstrated by a system or SoS typically does not yield all relevant associated phase space variables. Either not all of these state variables are known to the analyst or not all of them can be easily measured. In many non-laboratory real-world situations, it is often the case where only one system/SoS state variable $x(t)$ can be reliably sampled and measured as a function of time. It is possible to reconstruct an equivalent system phase space trajectory that preserves the topological structure of the original multi-dimensional phase space (i.e., the phase space attractor) via the dynamic measurement of only one scalar state variable via the use of *time-delay embedding* (*23*). In this technique, a sampled time series $x(t_0)$, $x(t_1)$, $x(t_2)$, $x(t_3)$,…, $x(t_i)$,…, $x(t_N)$ based upon time-interval-consistent measurements of a dynamical system is used to "reconstruct" the associated multi-dimensional phase space trajectory $\vec{S}(t)$ via the time-delayed approximation

$$\vec{S}(t_i) \approx \vec{S}_{delay}(t_i) = \left[x(t_i), x(t_i - \Delta t), x(t_i - 2\Delta t), \ldots, x(t_i - (m-1)\Delta t)\right]^T ,$$

where $\vec{S}(t_i)$ is the actual system state at sample time t_i, $\vec{S}_{delay}(t_i)$ is the time-delayed system state approximation at sample time t_i, m is the embedding dimension, and Δt is the time delay interval. The preservation of the original phase space topological structure is guaranteed provided $m \geq 2d + 1$, where d is the dimension of the attractor. Recursive application of the above approximation thus yields the phase space trajectory

$$\vec{S}(t) \approx \left\{\vec{S}_{delay}(t_1), \vec{S}_{delay}(t_2), \vec{S}_{delay}(t_3), \ldots, \vec{S}_{delay}\left(t_{N-(m-1)\Delta t}\right)\right\},$$

where N is the length of the original sampled time series. In this fashion, we can visually reconstruct the topology of system/SoS attractors from the original multi-dimensional phase space.

To illustrate the utility of time-delay embedding for the purpose of attractor reconstruction, we return to the example phase space for the notional flying insect depicted in figure 1. Suppose that the insect displacement coordinate is measured (under controlled conditions) once every 5 seconds (s) for a total time interval of 500 s (i.e., N = 100). Let us further suppose that a food sample exhibiting an appealing olfactory signal receivable by the insect via its antennae is positioned at a displacement 5.5 m from the insect's reference location. Assuming these operational conditions, figure 2 depicts a notional time history of the insect using two different data presentation formats. In figure 2(a), a set of purely notional time series data is presented that purports to measure insect displacement as a function of sampling time. From these data, the insect can be observed to progressively explore (in a semi-random fashion) regions of its environment further and further removed from the $d = 0$ reference location until settling around a displacement very close to 5.5 m. In figure 2(b), the same time series dataset is used to reconstruct the insect's phase space trajectory via time-delay embedding, where embedding dimension $m = 2$ and time delay $\Delta t = 5$ s. Within this two-dimensional phase space reconstruction, one can readily and easily observe the attractor (i.e., the point cluster surrounding $d = 5.5$ m) indicating a region of the environment that the insect seems to purposely adhere to (probably seeking nourishment from the food at that location)*. Although almost trivially simple, this example serves to illustrate how phase space attractors can effectively convey the possible presence of purposeful system behavior within an operational context.

* It must be noted that, in the current context, this displacement could actually indicate any point on the circle defined by $d = 5.5$ m. However, for the purpose of this example, we assume that the attractor center-of-mass displacement is identical to the location of the insect's food. In a more realistic application of this analytic approach, lat/long coordinates would probably be used in place of scalar displacement (thus increasing the value of embedding dimension m for phase space reconstruction).

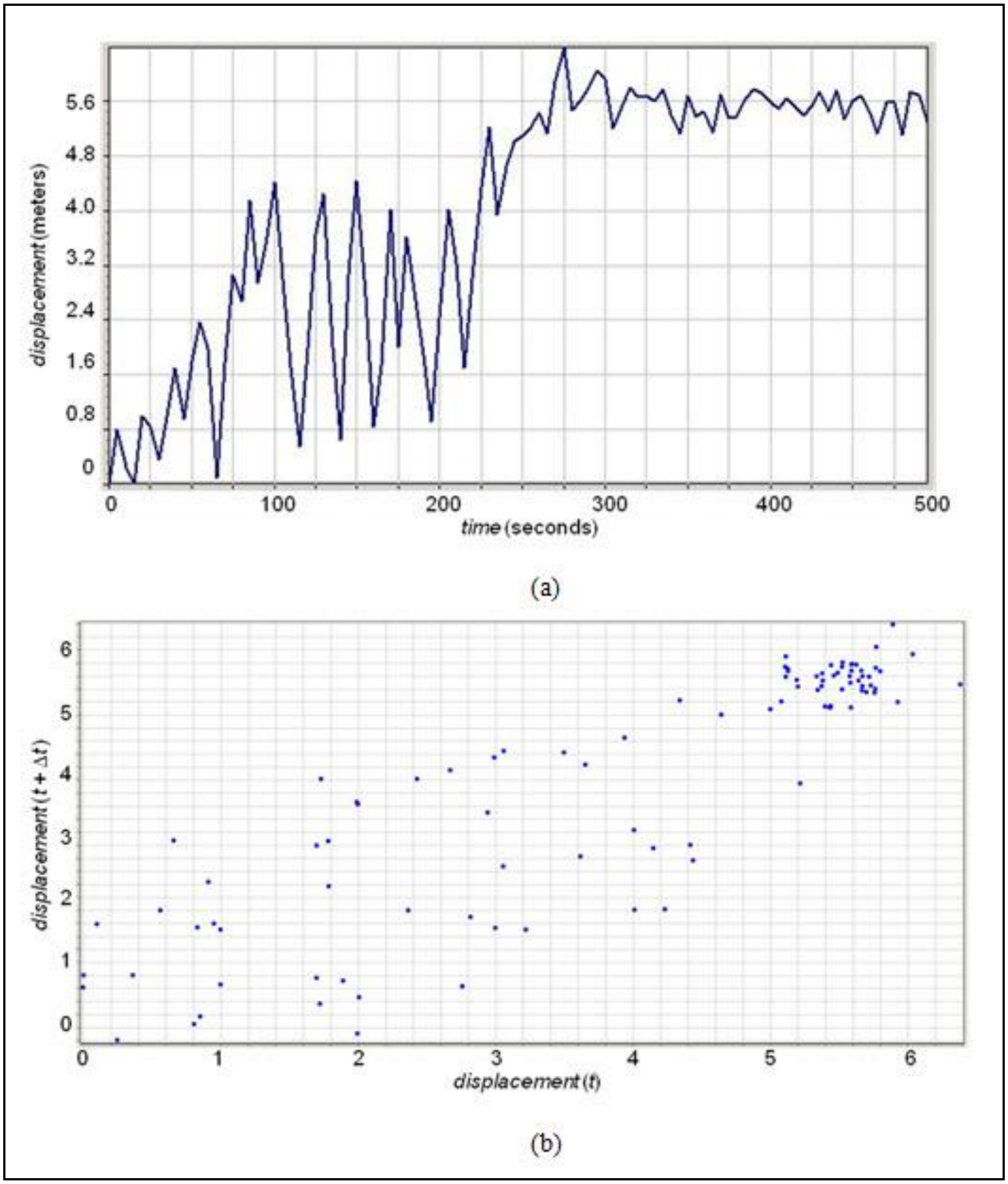

Figure 2. Dynamic response for the notional flying insect within an operational context. (a) Notional time series data presenting insect displacement as a function of sampling time. (b) The same dataset displaying displacement at time t versus displacement at time $t + \Delta t$.

Given an understanding of the nature of phase space attractors, the inquisitive analyst might next seek to explore exactly how a system or SoS might dynamically evolve towards such an attractor state as a function of phase space topology. This leads us to the related concept of a *basin of* *attraction*: the set of points within a system-specific phase space such that any initial conditions chosen in this set will dynamically evolve the system state towards a particular attractor. By allowing the intrinsic nonlinearity of a complex system (such as a SoS) to be manifested within an operational regime requiring detailed functional balance (to assure an achievement of purpose), the resulting systemic non-equilibrium can also lead to the coexistence of multiple attractors in phase space. This space can then be carved up into a set of attractor basins, where each basin corresponds to the set of states that, if the system were to start from there, would evolve to a particular attractor. The coexistence of multiple attractors and related basins of attraction within a phase space constitutes the natural mode of complex systems capable of demonstrating adaptive behavior and of performing regulatory tasks. We would thus expect to see the system staying within one basin of attraction (corresponding to resistance to change) and then at some point possibly switching between different attractors (corresponding to a change in the long-term mode of behavior) as the system strives to adapt in support of a purpose (or set of inter-related purposes). The existence of low-dimensional attractors associated with complex systems (e.g., the point cluster depicted in figure 2(b)) suggests the possibility of higher dimensional attracting structures within the phase space. Within the context of a military SoS, the challenge is to effectively exercise purposeful DMPs so that the phase space end-state location reflects the convergence of "Commander's intent" with an attractor, where all SoS initial conditions lie within the basin of attraction associated with this attractor. This would thus effectively demonstrate a purposeful navigation of the phase space by the SoS to achieve a desired goal (or set of goals).

When the constituent components within a dynamical SoS are exposed to some type of perturbative influence arising from the operational environment (e.g., noise or damage leading to functional degradation), the SoS is often driven away from whatever stable mode of operation it exercised prior to the perturbation. To compensate, the SoS will sometimes attempt to re-organize or re-structure itself without explicit pressure or involvement from other entities external to the SoS. This is the essence of the concept of *self-organization*: a process in which the internal organization of a system (typically an *open* system) increases in complexity without being guided or managed by an outside source (*24*). This change in organizational complexity can evolve in either time or space, maintain a stable form, or exhibit transient structural phenomena. During the self-organizational process, the SoS is purposefully self-motivated to explore its associated phase space in search of new attractors that arise when a system is driven away from its prior state of equilibrium. These new attractors exist within the basins of attraction of the SoS and are generally dynamically unstable, thus motivating the SoS to move purposefully along a phase space trajectory to a new attractor in pursuit of a return to operational equilibrium. Such a new attractor then constitutes the self-organized state of the SoS.

Once the inter-related concepts of phase space, phase space trajectories, attractors, and basins of attractions have been introduced, we can next focus our attention on the specific analysis of instances of complex systems within an operational context. This is accomplished via utilization of the system's *world line*: the phase space history of a system, synonymous with the phase space trajectory resultant from a specific dynamical system instance either as measured within the real physical world or via simulation. In general, a "world line" is the sequential path of measurable events (with time and state variables as dimensions) that marks the history of a system as it moves forward through time. In other words, a world line is a curve in phase space that traces out the (time) history of an object. One usually takes the proper time of an object or an observer as the curve parameter *t* as measured along the world line. Finally, given the inherent uncertainty often present upon measuring the state variables describing a time-evolving complex system, the concept of a world line may be extended into:

- a "world sheet" reflecting uncertainty within a single measured state variable, and
- a "world volume" reflecting similar uncertainty within two (or more) state variables.

For example, the world sheet and world volume associated with a system exhibiting positional uncertainty is depicted in figure 3.

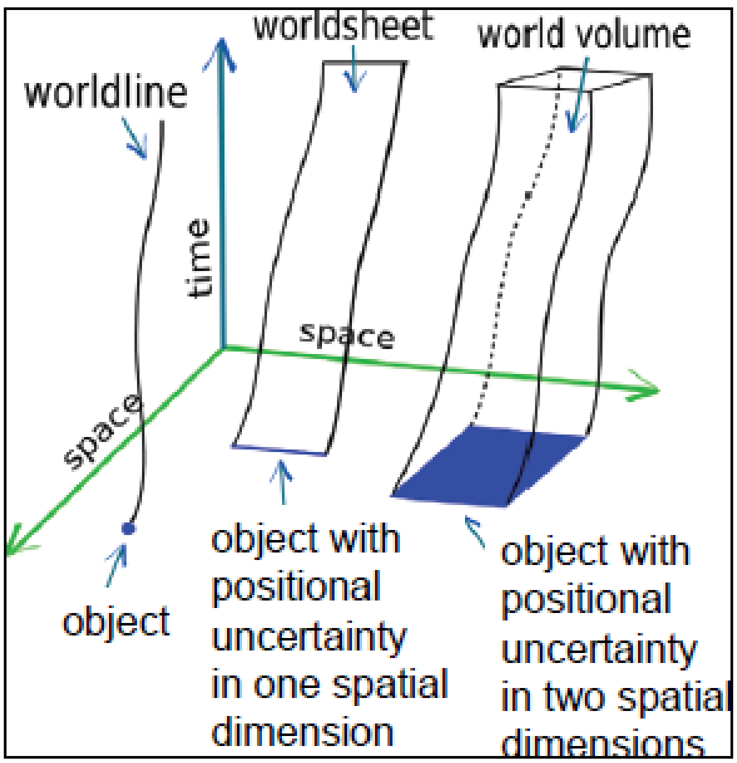

Figure 3. World line, world sheet, and world volume associated with the time-evolved states of an object with different degrees of positional uncertainty.

The following are several examples of system-specific world lines.

The time series data plotted in figure 2(a) presents a two-dimensional section of the world line for the notional food-seeking insect from our earlier example. Here, the insect's displacement

$d(t)$ is but one of three recordable metrics describing the dynamic status of the measured subject entity (the other metrics being velocity $v(t)$ and acceleration $a(t)$).

In a more practical example, the electronic logbook of a submarine (a computer software program that systematically records time-stamped materiel states, events, and conditions – including vessel position – via a network of distributed sensors) provides a description of the marine platform's world line. In this context, the world line allows one to calculate the speed of the submarine at any point in time during its deployment, given an available measure of distance (a so-called metric) appropriate for the curved surface of the Earth.

In a similar sense, an airplane's world line is captured by the associated flight data recorder (FDR) – popularly referred to as a "black box" – a device that records aircraft performance parameters as a function of time. The data recorded by the FDR can be used for purposes of analyzing air safety issues, material degradation, aircraft engine performance, and after-the-fact in-flight accident scenarios; such analysis essentially seeks to reconstruct the airplane's world line via FDR data.

For a simple phase space with three spatial and one time dimension, a curve is defined by four coordinate functions x_a ; $a = 0, 1, 2, 3$ (where x_0 usually denotes the time coordinate). A coordinate grid in this phase space is the set of curves one obtains if three out of four coordinate functions are set to a constant. We can extend the concept of world lines to represent the history of a real or simulated object within an N+1 dimensional phase space (or state space). In this mathematical space, there are N degrees of freedom defining scalar attributes associated with the object (e.g., latitude location, speed, weight, residual amount of fuel) and one degree of freedom associated with a time axis.

Within the context of a military SoS operating within a battle space, a world line is a quantifiable measure reflecting purposeful DMPs. We can thus characterize the evolving purposeful behavior of the SoS by measuring $\Delta_{CI}(t)$: the "distance" between the current phase space location of the SoS and the phase space location reflecting "Commander's intent" as a function of time. Successful progressive realization of this purposeful behavior by the SoS will demonstrate world line convergence upon the "Commander's intent" phase space locus via monotonically decreasing values of $\Delta_{CI}(t)$. On the other hand, monotonically increasing values of $\Delta_{CI}(t)$ will signify a disruptive challenge to the SoS's purpose. Finally, it would be of interest to investigate correlations between $\Delta_{CI}(t)$ for a SoS and any discernable phase space attractors representing consistently repeatable SoS end-states.

3.2.2 Homeostasis and Homeodynamics

To survive and remain functional within a challenging and often hostile environment, a complex adaptive system must maintain (within itself) a stable and sustainable operational structure. This property of such a system where it is able to maintain its essential state variables within limits acceptable to its own structure in the face of unexpected disruptive perturbations is called *homeostasis* (*25*). To maintain homeostasis, systems typically utilize a negative-feedback-based control structure. This involves a process of interaction that balances various influences and effects such that a stable system state or system behavior can be achieved and then perpetuated (*26*).

The homeostatic process existing within an adaptive system can be generalized into a negative feedback control block diagram as shown in figure 4. In this control circuit, which reflects the general structure of regulatory networks within the human physiology (*27*), a "controller" seeks to maintain the measured time-dependent system state variable $X(t)$ at a preset steady-state stable value X_{stable} in spite of incoming disturbance events impinging upon the system from a surrounding environment. The major components of the homeostatic process within the adaptive system include a sensor, a controller and an actuator.

- The *sensor* measures $X(t)$ at time ***t***, and then subtracts the reference value X_{stable} from $X(t)$ to generate the offset value $\Delta X(t)$.
- The *controller* accepts $\Delta X(t)$ as input, and then executes a decision-making process as a function of $\Delta X(t)$.
    - If $\Delta X(t) > 0$, then the controller formulates a process to *reduce* the value of $X(t)$.
    - If $\Delta X(t) < 0$, then the controller formulates a process to *increase* the value of $X(t)$.
    - If $\Delta X(t) = 0$, then the controller chooses to maintain the current value of $X(t)$.

Finally, the formulated control process is passed along as the controller output.

- The *actuator* accepts the recommended control process from the controller as input, and then physically implements this process in an attempt to modulate the value of $X(t)$. Finally, the modulated value of $X(t)$ exits the actuator, and the homeostatic cycle is repeated.

Asynchronously concurrent with this control cycle are incoming events from the surrounding environment that may act to negatively disturb the function of the actuator. These environmental disturbances, which can perturb the value of $X(t)$ away from X_{stable}, thus provide the need for homeostatic control in the first place.

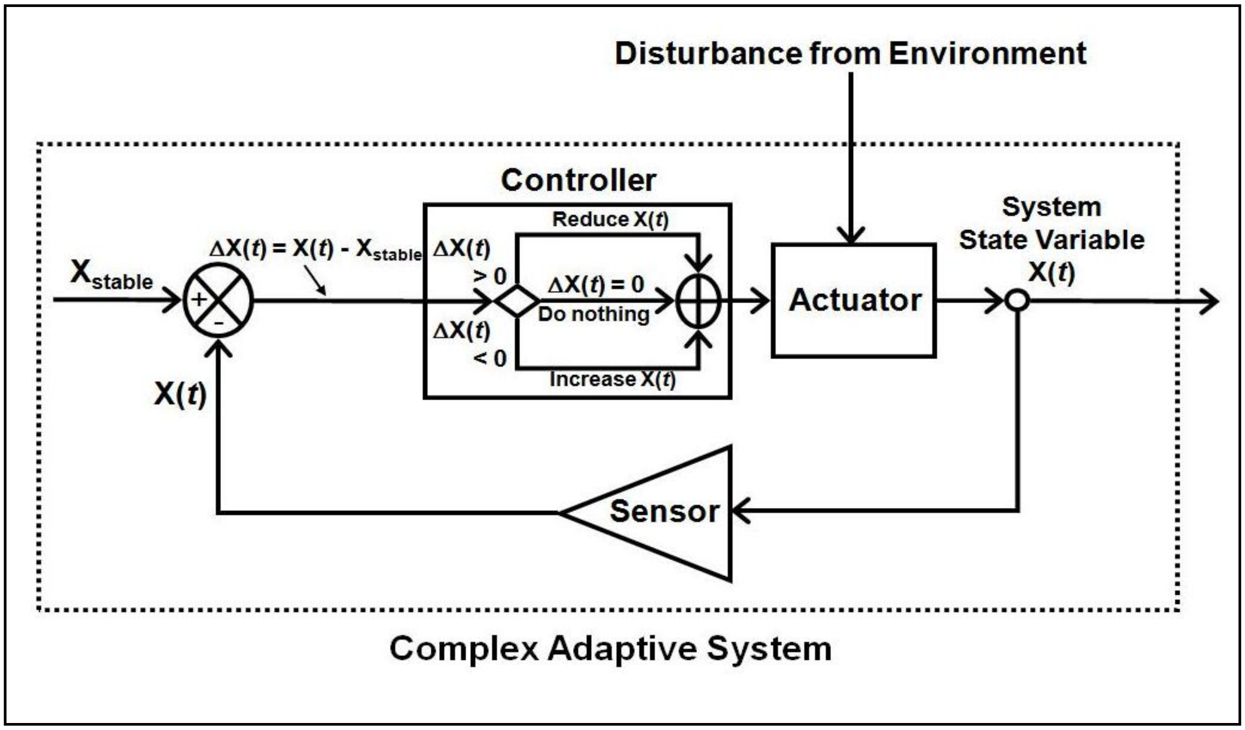

Figure 4. Homeostatic process within a complex adaptive system.

Homeostasis proliferates across a broad range of system types (both biological and artificial) of variable complexity and adaptive capabilities. The following are some common everyday examples.

- The ambient internal temperature of a house $T(t)$ can be disruptively impacted by environmental factors such as adverse weather conditions and heat loss from doors and windows. In order to stabilize house temperature, $T(t)$ is first sensed and measured at time t by a thermistor (as in a modern digital thermostat), and then passed to a controller. Next, $T(t)$ is subtracted from the thermostat set point T_{stable} to compute the offset value $\Delta T(t) = T(t) - T_{stable}$. Here, the controller output signal is constrained to open/close the flow valve supplying fuel to a furnace heater (i.e., the actuator). If $\Delta T(t) > 0$, the controller signals the furnace to close the fuel valve (and thus reduce $T(t)$). If, on the other hand, $\Delta T(t) < 0$, the controller signals to open the valve (to increase $T(t)$). Finally, if $T(t) = 0$, then the current fuel flow rate is maintained.

- Within a healthy human, the blood glucose concentration $C(t)$ is temporarily perturbed from a stable reference level C_{stable} (typically a narrow range from 90 to 110 mg glucose/dl blood) by vigorous exercise or the consumption of food. To counteract such disturbances and regulate blood glucose levels, the human body employs a very efficient homeostatic control process (*28*). A decrease in blood glucose concentration (where the offset blood glucose concentration $\Delta C(t) = C(t) - C_{stable} < 0$) is detected by alpha cells within the pancreas, which respond by secreting glucagon into the bloodstream. As glucose levels

> subsequently increase (to the point where $\Delta C(t) > 0$), the heightened blood glucose concentration level is next detected by beta cells (also within the pancreas), which in turn respond by secreting insulin into the bloodstream. The secreted insulin metabolizes the excess glucagon, returning $C(t)$ levels back towards the "normal" concentration range C_{stable}. In this example, the sensor, controller, and actuator functions required for homeostasis are all embedded within the pancreatic alpha and beta cells (responding to hypoglycemic and hyperglycemic blood concentrations, respectively).

In both examples, a single system state variable is homeostatically controlled at a time. Within a typical SoS, however, homeostasis might often involve stable control of a state vector $\mathbf{X}(t)$ of critical SoS variables (where $\mathbf{X}(t) = X_1(t), X_2(t), X_3(t), \ldots, X_N(t)$).

In the most general sense, homeostasis is typically manifested within open systems. To differentiate between the concepts of *open* and *closed systems*, we turn to the pioneer systems theorist von Bertalanffy.

> A system is closed if no material enters or leaves it; it is open if there is import and export and, therefore, change of the components . . . . A closed system must, according to the second law of thermodynamics, eventually attain a time-independent equilibrium state, with maximum entropy and minimum free energy . . . . An open system may attain (certain conditions presupposed) a time-independent state where the system remains constant as a whole . . . though there is a constant flow of the component materials. This is called a steady state (*29*).

Walker et al., provide further insight regarding the comparative limitations of closed vice open systems.

> (When exposed to environmental changes,) a closed system is, or becomes, locked or frozen in a particular state and requires no further import or export of information to maintain that state. A closed system (or industrial age organization taken to its extreme) is therefore unresponsive to environmental change, matched to an optimum means to an end within a defined context and slow to change or adapt. To use a computer science metaphor, a closed system is an entity that is 'programmed' while an open system is something that 'learns' (or programs itself) (*30*).

Although homeostasis can (by design) be present in both closed and open systems, the latter are better coupled to a surrounding environment, and are thus more adaptively responsive to incoming disruptive phenomena. Within a closed system, a homeostatic process will tend to oppose change using every available means; if the system does not succeed in reestablishing a stable equilibrium, it can disorganize towards a maximal entropy condition given its exposure to persistent functional disturbances. An open system, on the other hand, will tend to adapt itself to modifications of the environment and evolve (*31*).

An important attribute of complex spatially-distributed SoS is their dynamic self-organizing/self-synchronizing nature. Because the homeostasis usually present in this context is dynamically sustained, this type of control process is more properly referred to as *homeodynamics* (*32*, *33*). Instead of simply attempting to hold a SoS state variable (e.g., ambient temperature within a simulated ecosystem) constant, homeodynamics instead aims to actively reset reference values of control variables as a dynamic function of incoming information from the environment while simultaneously maintaining SoS organizational structure. Allowing for variation in reference stability levels brings adaptability into the homeodynamic SoS, as it can constructively respond to novel environmental conditions (*34*). Thus, homeodynamics characterizes an open (vice closed) SoS that can concurrently demonstrate both homeostasis and adaptive behavior (often at different space/time scales).

The generalized homeostatic process within a complex adaptive system depicted in figure 4 can now be "upgraded" to the similarly generalized homeodynamic process as shown in figure 5. As was the case with the system in figure 4, the homeodynamics in figure 5 is again constrained to the single system state variable $X(t)$ for purposes of simplicity and clarity. In this open complex adaptive system, a multimodal sensor array dynamically accepts information from the surrounding environment (e.g., in human physiology, sensory modalities are typically categorized as chemoreception, photoreception, mechanoreception, and thermoception). Then, the sensor array routes acquired environmental data into a fusion center (e.g., the brain that exists in multi-cellular organisms), where a composite informational representation of the sensed situation is created. Next, this situational representation is in turn routed to a DMP with the ability to adaptively reset the homeostatic reference value $X_{stable}(t)$ (the latter of which is now a dynamic function of a possibly changing situational representation as generated by the data fusion center). Once the adaptive DMP has decided to reset $X_{stable}(t)$ (or not), the updated value of $X_{stable}(t)$ (which may remained unchanged from the old value) is routed into the homeostatic process previously depicted in figure 4. Finally, the modulated value of $X(t)$ exits the homeostatic actuator (to guide complex system interaction with the environment), and the homeostatic cycle is repeated using the current value of $X_{stable}(t)$ until the latter is again reset by the adaptive DMP. It should be noted that, in the case of homeodynamics, the complex system is better suited to synchronously manage incoming disturbances from the environment that perturb actuator function.

Although a relatively new term in the scientific literature, the concept of homeodynamics is demonstrated by a multiplicity of well-known complex adaptive systems. Perhaps one of the best-known examples of a well-documented homeodynamic process is the alteration of the human body temperature stable reference level $T_{human/stable}(t)$ associated with a human demonstrating a fever. The increase in body temperature $T_{human}(t)$ during illness does not represent a control failure in a homeostatic thermoregulatory process. Rather, elevated levels of $T_{human}(t)$ are homeodynamically regulated by the brain (the source of the adaptive DMP in this example), so that conditions in the body where $T_{human}(t) < T_{human/stable}(t)$ are actively met with compensatory thermogenic processes (e.g., shivering, metabolic thermogenesis). In fact, the elevation of the control parameter $T_{human/stable}(t)$ associated with a fever is of benefit in mobilizing energy resources critically required when the human body combats infections (*35*). This example illustrates the close correlation that exists between homeodynamics and goal-directed behavior (i.e., destroying the invasive infectious agents within the afflicted human so to return the body state to a healthy normal condition). Finally, the homeodynamic control of a single system state variable in this example will very likely require extension to the control of a state vector $\mathbf{X}(t)$ when applying this concept to the adaptive management of a typical SoS.

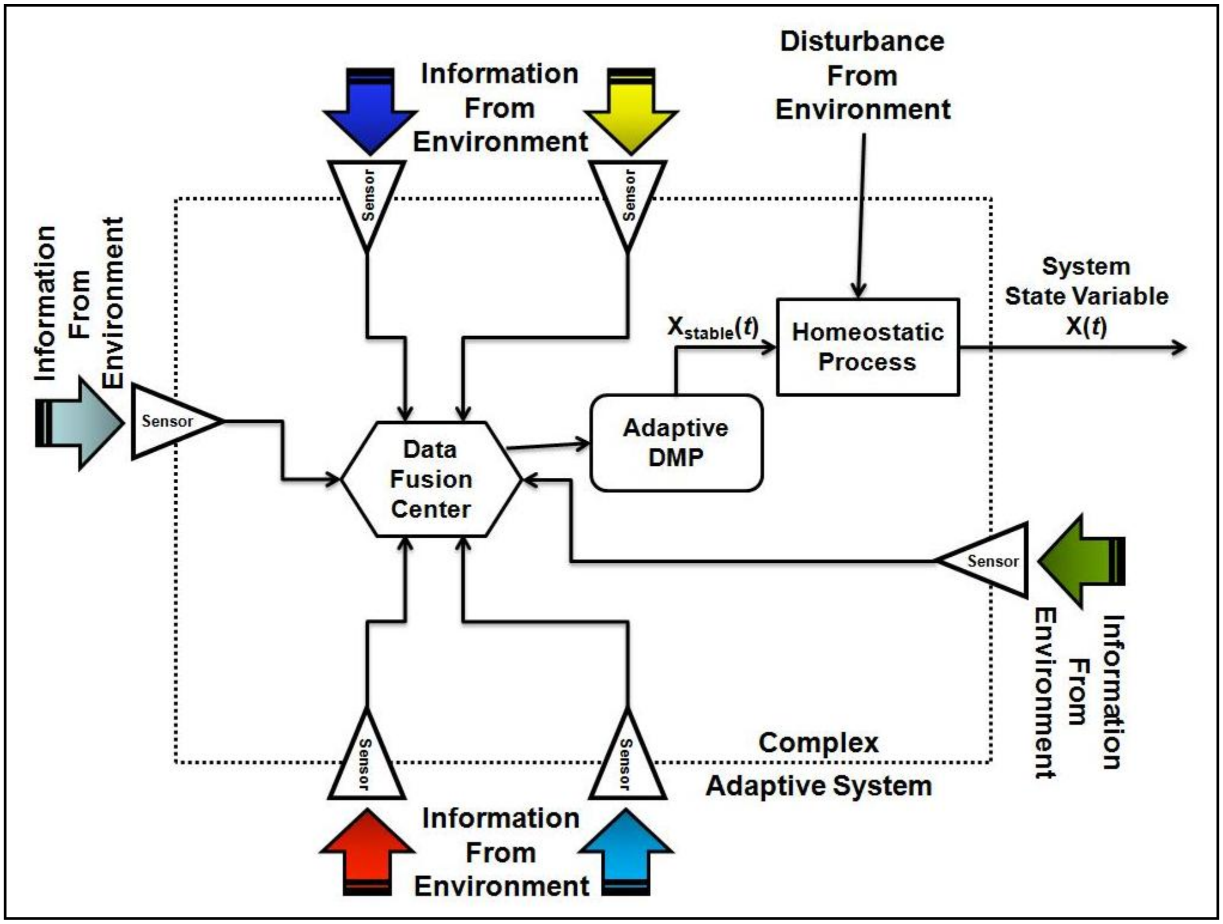

Figure 5. Homeodynamic process within a complex adaptive system.

With respect to a military SoS, there remains the question of how collective "self awareness" within and across the population of agents (both human and artificial) making up the SoS effects the organizational adaptive efficiency as a function of environmental disruptions. In the context of homeodynamic processes within a human, Miller (*36*) has proposed a qualitative measure he calls the *range of homeodynamic efficiency* (RHE): an abstract characterization of the relationship between environmental stressors (including physical, cognitive, and emotional types), the state of intra-human mind/body communication pathways, and homeodynamic effectiveness, the interactions of which determine potential adaptive outcomes of intentional situational management by a human under stress. Normally, there can be a fairly wide range of disruptions to mind/body communication pathway connectivity that humans can effectively tolerate while the overall human system remains relatively effective, but there are also danger points that put a person in jeopardy. RHE is also therefore a gauge of how effectively mind/body connectivity is maintained in the face of stress, which, in turn, determines how physically and mentally healthy a human is. Using this perspective, Miller (*36*) defines three general levels of RHE.

- *Ultra-stability*: Not the daily state of affairs, the highest level of mental and physical integration.
- *Average Functioning*: Makes allowance for stressors and some communication pathway disconnections that still allow for homeodynamic adaptation given minor illnesses.
- *Dehomeosis*: The most stress combined with the least connectivity among the elements constituting a mind-body system, usually resulting in a condition of moderately serious to severe illness.

If the environment itself is destructive or toxic to its locale then the adjustments demanded of a person will be harsher, and if homeodynamic adjustments are not possible the human system itself may follow a dehomeotic course.

Figure 6 illustrates a notional interpretation of the RHE measure as applied to a general organizational SoS (i.e., a heterogeneous military force). In this interpretation, RHE is a function of both

- the collective “self-awareness” that agents within the organizational SoS maintain concerning the operational status of other fellow agents, and
- the level of environmental stress (e.g., problems within the organization, disruptive events impinging upon the organization from hostile external agents).

Note that numerical values of RHE presented in the graph (along the vertical axis) are normalized to a relative level of maximal homeodynamic efficiency, and should be interpreted as qualitative vice quantitative measures of adaptive potential. Here, the organization may be considered “ultra-stable” given a very high level of shared situational awareness (SA) distributed amongst the SoS population, and a quiescent operational environment. At the opposite end of the scale, the organization is collectively in a state of “dehomeosis” when shared SA is at a minimum while the SoS attempts to operate within a very hostile environment. Assuming the validity of this collective interpretation of RHE, then a SoS is most effectively adaptive when SA is optimized across the organization (within practical constraints), particularly that information concerning the dynamic operational readiness levels of organizational peers.

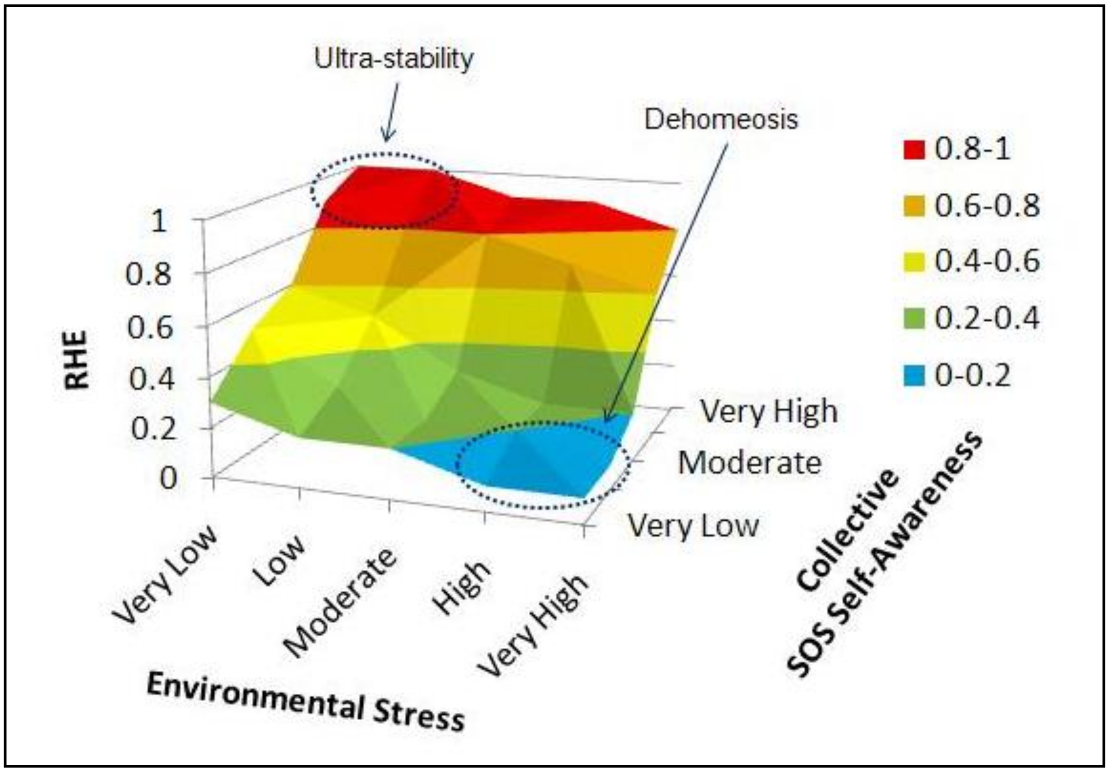

Figure 6. Range of homeodynamic efficiency (RHE) for a general organizational SoS.

3.3 Sociotechnical Systems Theory

One existential property of a military SoS is that it is a sociotechnical system. Sociotechnical system properties are present in any military SoS (*37*, *38*). In a military domain, decision making and its consequences are central to the function of the SoS (*13*). As a rule, in a military SoS, people (leaders) make decisions and warfighters use technology to realize their purpose and accomplish the task. We therefore hypothesize that, if decision making process and decisions made are the bounds that will determine how one can decompose a military SoS, then any perspective from which to view the military SoS needs to recognize the sociotechnical properties present in a military SoS.

The purpose of this section is to highlight the sociotechnical aspect present in both military and non-military SoS. Sociotechnical systems refer to the interaction between the technical system and the human. Given a base of knowledge it is the socio part of the system that applies this knowledge to satisfy local variations, using the technology in the system. The technological part of the system may have a small range of adaptation, but with people in the system a wide range of adaptation is possible and in a military system this is the norm. In most definitions of SoS the notion of dynamicism induced by human action is only present by implication. The interoperability between the people and technology in the system makes for adversarial SoS in a competitive environment such as the military.

Sociotechnical systems theory is about the behavioral aspects of people and the technical aspects of technology. When people and technology interact the outcome is both predictable and unpredictable. The predictable interactions are pre-engineered "cause and effect" relationships. The socio (people) does not behave like the technical (machines) in the system but the interdependence of the socio and technical behavior in the system lends to the undersigned non-linear relationship in the system that affects the system's performance. Consequently, neither the socio nor the technical aspect of the sociotechnical system can be optimized individually. The aim of the sociotechnical systems approach is to maximize both the outcome of the technical system and the people working in the system (joint optimization).

A network enabled military system consists of decision making people using networks (technology) to make informed decisions in a competitive dynamic environment. There exists a parallel between the military command and control and the design challenges that sociotechnical systems theory was developed to answer. In order to survive, any social system must demonstrate the following four functions: (1) attainment of organizational goals, (2) adaptation to the environment, (3) integration of personnel activities, and (4) maintain continued existence of critical organizational roles via recruitment and socialization. This is true in the military domain also.

To achieve these system functions, Cherns (*37*, *38*) advocates the following ten design principles for sociotechnical systems.

1. *Compatibility*: The design of the system must be compatible with the system's purpose. However, including the objectives of everyone in the system can lead to conflict, so consensus decision making by the designers of the system is essential.

2. *Minimal Critical Specification*: To keep system flexibility, specify only those parts within an organization that are essential to support purpose and do not specify non-essential elements. When non-essential elements of a system are specified, the system's flexibility is constrained and the system cannot adapt to changing environmental conditions.

3. *Variance Control*: Variance in sociotechnical terms is an unexpected unaccounted event that affects system outcomes. Variance Control principle states that variance needs to be minimized and unplanned events must be controlled as close to their point of origin as possible.

4. *Boundary Location*: Boundary Location relates to boundaries between departments. The principle requires that the departmental boundaries within an organization should *not* impede the sharing of information, knowledge, and learning.

5. *Information Flow*: This principle deals with the dispersion of information in the system. Information should be available as needed. This principle assumes that organizational information can be used for control, records and action.

6. *Power and Authority*: People who require resources to execute their purpose should have access to them and the authority to command them. Another aspect of this principle is that people who have access and authority over the resources should be responsible for them and their use.

7. *Multifunctional Principle*: This principle describes the adaptability of the system. Elements of organizations must adapt to their environments, of which the most important are usually other organizational elements. Adaptation can be via adding new roles or by modifying current roles.

8. *Support Congruence*: This principle refers to the desired similarity between reward systems and management philosophy. The systems of social support should be designed so as to reinforce the behaviors which the organizational structure is designed to elicit.

9. *Transitional Organization*: This principle addresses organizations undergoing redesign experience and is in a state of change. It is assumed that the transitional organization is both different and more complex than either old or new.

10. *Incompletion*: Design is a reiterative process and the closure of previously-considered options opens new one. The main idea purported by this principle is that stability is just a moment between transitions and all systems should be able to evaluate and redesign to a changing environment.

The sociotechnical system is one method for designing organizations and work systems and this method is characterized by the balance of human behavior and technological elements in the organization. The design principles aim to jointly optimize people and technology that forms the initial conditions for effective network enabled military system. The sociotechnical systems theory helps define the notion of shared awareness, peer to peer interaction and adaptability in the network enabled military domain.

The classic command and control (C2) model assumes deterministic behavior in the system where the whole is equal to the sum of the parts, the outputs are a known function of the inputs and the results are repeatable from one application of the model to the next. A recent model of C2 developed by the North Atlantic Treaty Organization (NATO) working group SAS-050 (*19*) provides three major axes (and a three dimensional space) within which various instantiations of C2 can be plotted. The purpose of defining the problem space in terms of these three dimensions is to explore alternative paradigms for C2, ones that are becoming increasingly tractable with the growth in networked technologies. The formally rational instance of classic C2 is positioned in the NATO SAS model as shown in figure 7. This type of organization might be characterized by unitary decision rights (in which optimum means to ends are specified at the top of, or at higher levels of a vertical hierarchy); tightly constrained patterns of interaction (due to rules, standard operating procedures and other means by which an organization specifies optimum means to ends) and tight control (in which performance can be quantified and controlled through intermediate echelons of management).

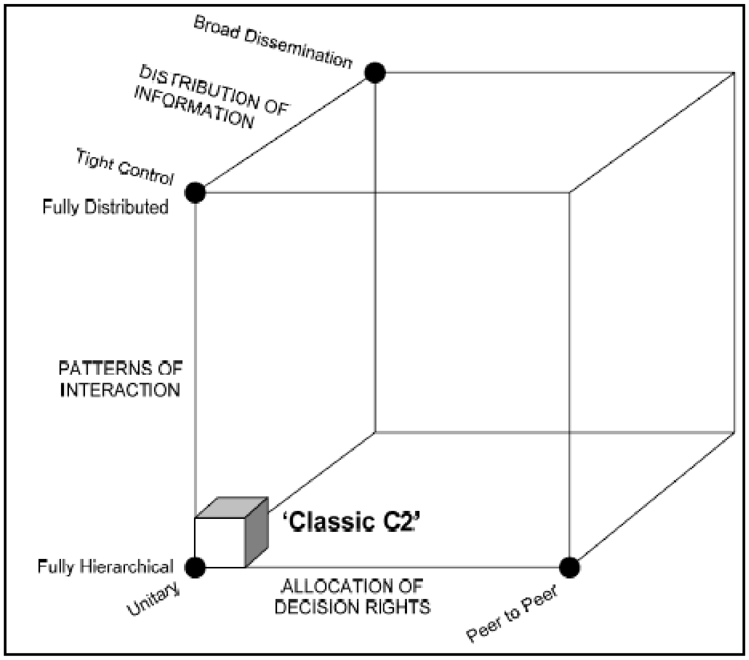

Figure 7. The NATO C2 conceptual model.

A future network enabled force empowers individual units to interpret the broad command intent and evolve a flexible execution strategy with their peers (*39*). The sociotechnical principles provide a basis to study the human aspect of such a SoS. A military SoS is not a sociotechnical system in its entirety. The guiding principles of a sociotechnical system emphasize the need to maintain a steady state between people and product. In the military domain the primary focus is to produce a fighting force that can adapt using information attained from the environment and previous knowledge bases while maintaining self synchronization and peer-to-peer interactions.

3.3.1 Multiscale Analysis of Complex Systems

SoS can have complex systems as subsystems. Consequently, a study of methods to analyze complex systems can provide insight in the analysis of SoS. A complex system is composed of interconnected components that are assembled together to achieve a system behavior that cannot be attained from the individual parts that make the complex system. Defense systems consist of systems that have nested purposes that the individual systems must accomplish to satisfy a higher purpose.

Scale and complexity are inherent characteristics of a complex system. Each system is ideal for the context/environment/expression for which it is designed. Its effectiveness is limited when the context is changed/modified as it cannot perform all the actions it is designed to take. The components of the system interact to complete a task. The interaction and coordination between the components vary under different conditions. The behavior of the system is the coordination of the components that comprise that system coupled with the human action employing those components. The number of components that must act together to complete a task is the *scale* of the task. A system is expected to take distinct actions to complete a task. *Variety* is the measure of the distinct actions that the system can take to complete a task. Multiscale analysis of complex systems builds on the twin recognitions that scale and variety/complexity are necessary for effective performance of complex systems, and is the focus of the remainder of this section (*40*).

Components in a complex system either work in a coordinated way or independently. When the components of the system coordinate with each other, the possible number of distinct actions that the components can take is constrained. Coordination reduces variety. A system exhibits high behavioral variety when the components in the system work independently of each other. Additionally when mesoscale/macroscale collective behavior is required from a system, the components in the system have to act coherently. Increasing the variety for one desired scale (coordination of components) is possible only when variety is constrained for another scale (grouping of components). This implies that there are various degrees of tradeoff that are possible to achieve the desired level of behavioral variety from a system.

The key to multiscale analysis of the behavioral variety of any system is that the components of the system have a limit or bound on its variety. If the components of a system coordinate other components of the system then there has to be limits on what the organizational structure can do. It is possible that the variety associated with the coordinated system exceeds the variety of the components. A microscale system with independent decision making components has a high behavioral variety. As the system size increases, the coordinated system behavior of the individual components reduces the behavioral variety of the encompassing system. Complex systems have an increasing behavioral variety as the system scale decreases due to coordination at various scales.

For a system to be successful its components must be able to work independently and with each other. Certain tasks can be accomplished only when a specific number of the system components work together. The key issue is in determining the number and components that need to work together to accomplish the task. Coordination between components in a system is possible only when there is information flow between the components that make up the system. At the same time communication and coordination also reduces the behavioral variety of the whole system. An understanding of this relationship between scale and variety helps us develop a method to analyze SoS. However, it is not the solution because, in information driven military SoS, the human components in the system adapt themselves and technology based on the information feedback to every action taken. In terms of multiscale analysis this change in component systems is equivalent to a change in the whole system.

4. A Concept of SoS Analysis

Multiscale analysis of complex systems shows us that each of the components has a limit on its variety. When components making up a complex system are acting in a coordinated way, they cannot act independently. In a SoS, units often modify the assets (component systems) provided to them to survive in a hostile environment. This change of component systems makes traditional multiscale analysis technique inadequate for defense SoS.

Purposeful system analysis technique usually involves explaining the component system behavior, as in analytical thinking, but this method fails for military SoS. The reason for failure is that most military SoS are scenario dependent and the systems in the SoS are driven by nested concepts and inter-related purposes in conjunction with a commanders intent and concept of operation. Such a SoS loses its essence when it is taken apart or decomposed for analysis. There is both a time component and information uncertainty when decisions are made in a military SoS. Analysis techniques that include adaptive decision making by complex systems is one possible approach to analyze a system in the SoS. However, if any original system(s) in the SoS is modified/altered the SoS is altered and the analysis technique is inadequate.

Weapons and equipment are often physically and operationally modified/adapted by the warfighter to better suit his objective in a hostile environment. In a military SoS, systems are adapted by warfighters to improve their survivability and to achieve their commander's intent and at another level of abstraction the warfighters are lost to the overall SoS by death and other types of losses. For such a system, we hypothesize that analysis of a SoS is two-fold where the analysis takes into consideration the variety and scale of the SoS in a scenario dependant model and then uses nested concepts and inter-related purposes to integrate to form composite and holistic analysis of the SoS. Furthermore, we contend that if this hypothesis is accepted then the output of a SoS model can only be probabilities of possibilities.

5. Conclusions

SoS is a term that has been used frequently in literature to describe systems in many domains. A number of people have grappled with the issue of what *is* and *is not* a SoS. Our interim report proposes that one can view any, and especially military, SoS as possessing fundamentally three salient features, they: (1) are social technical systems, (2) are purposeful systems, and (3) possess a defined and purposeful relationship among all elements. It is ultimately the interplay of these salient features that determines the shape of any analysis of these SoS.

First, they are sociotechnical systems that possess some observable structure, for example, a brigade combat team, or a business entity of some size. As the term implies, the human element provides many of the emergent capabilities often associated with a SoS, and the technical elements augment, facilitate, or otherwise promote these emergent capabilities.

Second, military SoS are at their very core, purposeful systems; that is, they are not created as static structures, but dynamic entities that must drive to a desired end state that emerges from their collected purposeful activity. While they may be “cobbled together” from erstwhile previously independent pieces, or designed from scratch with specific properties, they all have a purpose, an aim, a goal they desire to achieve. All the social and technical elements that comprise a given SoS must derive their activity from their knowledge of the SoS purpose, and ultimately, their role in achieving that purpose. Whether they are a private driving a tank, or the general commanding the brigade combat team, it is this collected purposeful activity taken in light of their perception of local realities that ultimately determine their end state.

Third, while each SoS is a purposeful system, and one can view each entity within a SoS as a purposeful system, it is the explicit or implicit relationships between the elements within a SoS that ultimately determine its emergent properties. One can view these explicit or implicit relationships as an expression of “nested concepts and inter-related purposes.”

Existing analysis techniques apply largely to non-changing systems. Human behavior is unpredictable when threatened. Analysis of such SoS is an interplay between a system level intent, a purpose, and the activities of the myriad elements that comprise that SoS. The notion of “nested concepts and inter-related purposes” allows both the military commander and the analyst to form progressively smaller concepts that collectively describe an intermediate end state in service to the larger goal, and collected relationships among the entities who must realize that concept. By availing themselves of this paradigm, the analyst can both decompose the SoS into more easily understood components and then synthesize their results into an overall assessment.

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List of Symbols, Abbreviations, and Acronyms

C2	command and control
COA	course of action
DMP	decision-making process
FCS	Future Combat System
FDR	flight data recorder
NATO	North Atlantic Treaty Organization
RHE	range of homeodynamic efficiency
s	second
SA	situational awareness
SoS	system of systems
SoSA	SoS analysis

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