

## Engineering Complex Systems@MITRE

### What Is a Complex System?

A complex system can be characterized as one whose development and maintenance are complex, one whose behavior is complex, or usually both. Often, the term “enterprise-wide” is used to characterize a complex system. This term can signify a global business enterprise as well as collections of systems that interact across their individual boundaries to achieve some common goal.

Examples of complex systems

include biological systems, ecological systems, societies, as well as the systems that humans create and use. At MITRE, the complex systems we most frequently confront are those that must be developed for human decision makers and have information exchange as an essential capability.

Some salient features of complex systems, as described within MITRE and in the literature, include: \*

- Complex systems are usually enterprise-wide systems that are constructed by the integration of multiple separate systems. Participants must merge their individual goals and behavior to meet the goals of the enterprise to which they belong.
- Many participants have existing systems, cultures, or practices in place that are in conflict with those of other participants and are not easy to change.
- The requirements for the system are not precisely known at the start and dynamically change with time.
- Interaction among the system's components and with its environment can produce behavior that is not always predictable or explainable from observing the behavior

of the components alone. Cause and effect relationships for the system as a whole are often not obvious.

- Complex systems can have a significant human component, which contributes to the complexity of the system behavior and its change over time.
- Both the organizations that use complex systems and the systems themselves must manage change to effect the desired enterprise behavior.

... complex systems can exhibit self-organization with decentralized control, emergent behavior, and adaptation to their environment over time.

In summary, complex systems can exhibit self-organization with decentralized control, emergent behavior, and adaptation to their environment over time.

\* Sources of these definitions include Judith Dahmann, Len Wojcik, Garry Jacyna, Jim Hill, and Renee Stevens of MITRE; J. J. Henrik in *Complexity Theory and Network Centric Warfare*, James Moffat, Department of Defense Command and Control Research Program, CCRP publication series, September 2003.

#### About this issue ...

In this issue we look toward the future of systems engineering to deal with the complexity of enterprise-wide applications. Systems engineering has become a topic for research, innovation, and improvement in industry and academia. What makes systems engineering more difficult today is the confluence of many attributes that characterize what has been called “enterprise systems engineering,” “system-of-systems engineering,” “complex adaptive systems engineering,” and other terms. All address the complexity of the systems engineering processes and the systems themselves.

# Modeling and Simulation (M&S) Support for Enterprise Systems Engineering

Modeling and simulation (M&S) provides a capability to explore requirements and design options and iteratively improve understanding of their consequences. This is

**MITRE is experimenting with techniques for developing simulations of complex systems and analyzing the results.**

particularly relevant to complex systems, for which it is difficult and expensive to implement and test all options. M&S is now being used more broadly to

model and analyze complex systems such as market behaviors, social behaviors, biological systems, and other applications in which emergent behavior can be studied.

MITRE has been performing research and experimentation in the use of M&S for studying future operational concepts for air traffic control and military strategies and to study human behavior in decision making as part of a complex system. MITRE has also been experimenting with techniques for developing simulations of complex systems and analyzing the results. These methods include agent-based modeling (ABM), data mining, data farming, and interpretation of ABM results. Project Albert (see page 5) and multi-fractal data analysis are two efforts to analyze data from simulations.

At this time, ABM of complex adaptive systems and related approaches have been helpful to system under-

standing, but practical applications to policy and operational issues in aviation and defense are still rare. Validation of ABMs (emergence versus convergence) is challenging. Matching the level of ABM to the issues can be delicate:

- Too much complication is not worth the effort and may confound understanding.
- Too little fidelity yields inapplicable results or insight.

MITRE recognizes the potential of ABM and related approaches and will continue research in these areas.

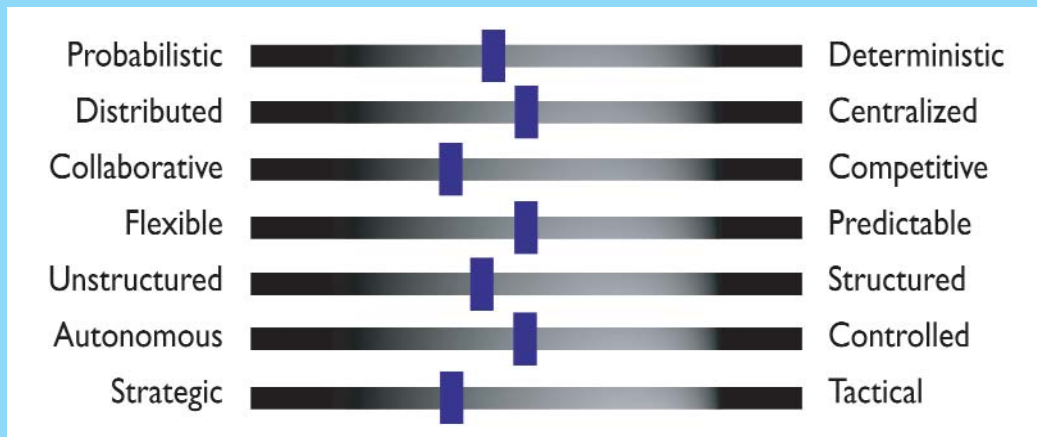


For more information, contact Dr. Judith Dahmann, [jdahmann@mitre.org](mailto:jdahmann@mitre.org), 703-983-1363.

## Where will the balance be?

System paradoxes that do, or will, exist in complex systems.

Trying to do away with, or ignoring, any system paradox is probably not a good idea.



# What Seems to Work Well ... and Not So Well ... for Complex Systems

## What seems to work for complex systems includes:

- Using engineering enablers, including architecture, visions, and plans (as long as they are viewed as means rather than the end itself).
- Facilitating continuous, broad-based involvement by representatives of key stakeholders from multiple organizations. This works best when supported by senior leaders of the represented organizations.
- Building consensus around the enabling infrastructure and design tenets.
- Using early field trials and experiments to help explore how the elements work with one another and to introduce “real world” dimensions.

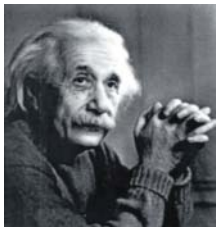
## What does not seem to work as well for complex systems includes:

- Developing detailed and comprehensive requirements specifications.
- Paying insufficient attention to understanding the larger environment in which the complex system will operate and evolve.
- Failing to involve all the key stakeholders.
- Establishing unnecessarily complex organizations and overemphasizing process over progress.
- Developing a grand design and expecting it to remain constant in the face of technology obsolescence, changing user expectations, emerging behavior, and evolving mission environments.
- Proposing technical solutions for inherently nontechnical problems.
- Acquiring capabilities that cross traditional program boundaries.

## Based on these observations, a preliminary set of implications for engineering complex systems is as follows:

- Place less emphasis on having a comprehensive, detailed set of requirements and specifications at the onset and more emphasis on incremental experimentation and trial.
- Build consensus around the enabling infrastructure and design tenets to guide the evolution of the system.
- Make maximum use of existing collaborative engineering tools and practices and encourage the evolution of new techniques.
- Plan to spiral off useful capabilities to users.
- Recognize and encourage the system to evolve in situ.

For more information, contact Renee Stevens, [stevensr@mitre.org](mailto:stevensr@mitre.org), 703-983-6013.

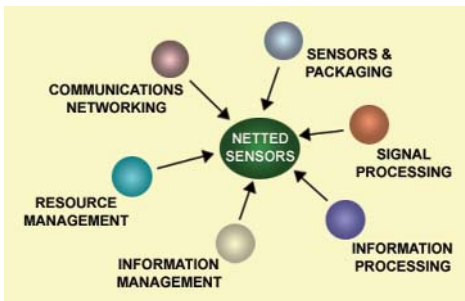


**“Any intelligent fool can make things bigger, more complex ... It takes a touch of genius and a lot of courage to move in the opposite direction.”**

*Albert Einstein*

# Exploring Network Centric Sensing to Solve Complex System Engineering Challenges

Sensors have evolved from being homogeneous, mission-specific units connected to a network using centralized control, processing, and decision making to complex, “collaborative” Network Centric Sensing (NCS) systems, also known as Netted Sensors (NS), to address difficult problems. NCS require that groups of sensors have overlapping coverage and collaborate to provide the best integrated (fused) picture and through the power of the network expedite the development of actionable knowledge.



Focus on Collaborative Processing

The NS vision is that networks will contain a very large number of heterogeneous sensors that will be flexible and adaptable to support many simultaneous missions, and they will address future unforeseen problems. We will have networks of networks of sensors, where the number of heterogeneous sensors and platforms will be dynamically changing. The types of sensor platforms and sensors nodes will range from smart devices (connected via the Internet) and proximity micro-sensors, to large sensors on standoff

platforms all connected via networks. NCS work is in the early stages and contains complex system engineering challenges; the transition from evolutionary to transformational capabilities is a few years away. In fact, significant NS research and development challenges exist in the areas of sensors and platforms, communications and networks, signal and information processing, resource and information management, and security.

MITRE is helping our government sponsors understand the potential of netted sensors and how they can be integrated into systems to address problems such as asymmetric threats and homeland security. MITRE has established an NS corporate initiative under the MITRE Technology Program (MTP) with contributors from the Center for Enterprise Modernization (CEM); the Center for Integrated Intelligence (CIIS); Washington Center for Command, Control, and Communications (WC3); and the Center for Air Force Command and Control Systems (CAFC2S).

The NS program brings together a team of highly capable staff from many disciplines across MITRE to work on common problems. The project requires an interdisciplinary research and development team because sensing, processing, communication, information management and resource control are all interdependent and embedded in a sensor network.

The project has three components: research, the development of a robust test bed, and the demonstration of concepts, technology, and solutions relevant to our sponsors. This year the project is demonstrating detection of people and vehicles and how to classify each object, for example, recognizing a bus, a truck or a civilian vehicle. This type of classification ability is applicable to situations like border security. The second-year demonstration will incorporate object tracking and identification components (a two-dimensional problem). The third year will incorporate locating a target on a surface, locating its height off the surface, and identifying it as fully as possible (a three-dimensional problem). This type of capability is crucial in urban terrain environments, which is one of the most challenging environments.

The project will yield new technology, demonstrate NS capabilities, and produce a usable laboratory tool suite. It will also lead to a better understanding of how NS technologies apply to MITRE’s customers and how to leverage commercial investments to solve our sponsor’s unique challenges.



For more information on the netted sensors initiative, contact

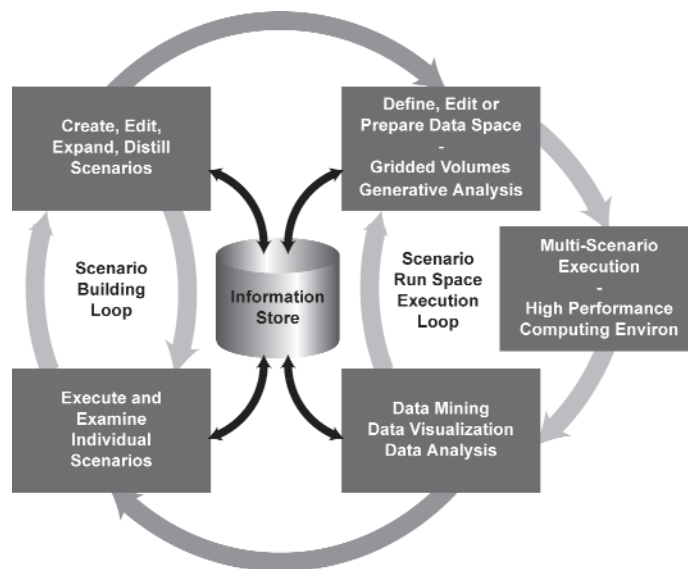
Dr. L. Danny Tromp, [ldtomp@mitre.org](mailto:ldtomp@mitre.org), 781-271-5450; or Dr. Garry Jacyna, [gjacyna@mitre.org](mailto:gjacyna@mitre.org), 703-983-6972.

# Project Albert - MITRE Support

In 1998, General Charles Krulak, then Commandant of the Marine Corps, recognized the inherent non-linearity of war and that many of the existing combat models and simulations were archaic or inappropriate given the asymmetric nature of modern combat. For a few years leading up to his comments, the United States Marine Corps (USMC) led the development of ideas to capture answers not provided by traditional models.

Project Albert is the USMC's effort to leverage new technologies and sciences to enhance decision support by applying new modeling methods, associated analytic tools, and the technique of data farming. Data farming is the process of using high-performance computing to execute a model over a large parameter space in order to gain insight into the full breadth of potential outcomes.

A MITRE team is working with the Marine Corps and other Project Albert collaborators to develop and refine the methods, concepts, and technology of data farming to support operational applications. This work spans various avenues of research, including agent-based modeling and model construction, high performance computing technologies, data mining capabilities, design of experiment research, and high-dimensional data visualization.



Data Farming Loop

Another focus of Project Albert is to research and prototype the interfaces and architectures, human and software, which will allow modelers to easily submit and execute models, design experiments, and collect and explore the results.

MITRE supports Project Albert in addressing real questions. MITRE team members have built models or provided analysis of data farming results to seek insight into questions such as:

- When is decentralized (vs. centralized) command and control desired or preferred?
- What is the role of trust, or other so-called “intangibles,” on the battlefield?
- How can we best protect our homeland from a martyr-based offense?

- How can a bio-terrorist attack be mitigated in a free society?
- What system characteristics are important in military convoy protection systems?
- How can groups co-exist peacefully?

Project Albert is not about running specific models for predicting a final “answer.” Project Albert is about data farming any model to gain insight into potential outcomes and experimentation with emerging methods. Data farming, by providing the ability to process large parameter spaces, makes possible the discovery of surprises (both positive and negative) and potential options.



For more information, contact Ted Meyer, [tedmeyer@mitre.org](mailto:tedmeyer@mitre.org), 703-580-4343.

# Multi-agency Planning Workbench and Toolkit for Complex Systems Architecture Analysis

MITRE's Center for Enterprise Modernization, is exploring the issues surrounding enterprise modernization planning in a multi-agency environment. The objective is to support integrated mission and information technology planning, covering enterprise strategic plans, performance management, investment plans, and information resource management plans, through more detailed representations of mission activities and business processes that are coupled to the Enterprise Architecture. Architectures represent all dimensions and the full complexity of the enterprise as a "Genomic Code."

Increasingly, government initiatives such as homeland security, managing the international flow of goods, and people, health services, and joint missions require groups of agencies to work together at the mission and organizational levels, as well as at the information system support level. The collaborating agencies typically have incompatible architectures at varied stages of development and sophistication. Key aspects of successful interagency collaboration depend also on the interplay of humans and organizations, as well as information technology (IT) and non-IT systems, forming a workflow or activity network.

Issues adding to the system complexity include timing, synchronization, priorities, bandwidth, systems compatibility, and agency-unique syntaxes. The syntax issues exist at the organizational, data, and information exchange levels, with information exchange syntax differences impacting both human and machine information exchanges.

The Multi-agency Planning Toolkit uses activity process models of several commercial varieties, as well as static information architecture products conforming to defined architecture frameworks, integrated in a Geographical Information System (GIS) Workbench environment. Our goals are to:

- Find ways to easily move architectural and process information between the static architecture environments and the dynamic process model environments that describe mission performance—the Executable Architecture concept.

Key aspects of successful interagency collaboration depend also on the interplay of humans and organizations, as well as information technology (IT) and non-IT systems forming a workflow or activity network.

- Identify major gaps and deficiencies in the architectures of agencies involved in important multi-agency missions.
- Explore environment to environment level interoperability using process models built in different commercial-off-the-shelf (COTS) environments.
- Evaluate organizational readiness to interoperate.

Integration of a heterogeneous COTS environment will support existing models and architectures from individual agencies as active components of a larger multi-agency planning environment.

The impact of this research will reach virtually all of MITRE's sponsors. Since all federal agencies are developing Enterprise Architectures, and most typically must interoperate with other federal agencies, a demonstration of the capability to dynamically examine their architectures integrated with other agency architectures will significantly improve their mission/business planning, performance planning, resource allocation, and investment strategy and decision-making processes.



For more information, contact Dr. Kenneth Hoffman, [khoffman@mitre.org](mailto:khoffman@mitre.org), 703-983-5613; or Dr. Thomas Pawlowski, [pawlowst@mitre.org](mailto:pawlowst@mitre.org), 913-684-9139.

# Learning Tactics for Swarming Entities

Modeling and simulation (M&S) is becoming an increasingly important technology for various programs seeking to develop and assess new military concepts or design and acquire new military systems. Two important examples are the Department of Defense initiatives in Simulation Based Acquisition and Joint Experimentation. In each of these application areas, new ideas are systematically explored in order to understand their capabilities and limitations: What are the conditions under which a system or concept succeeds or fails? What are the most effective ways to exploit a new capability or counter a threat? What can a threat do to effectively respond to our new capability? The innovative ideas and creative thinking needed to answer these questions are typically supplied

by knowledgeable engineers and military personnel. However, the set of all possible threat reactions or tactical innovations is typically too large to evaluate exhaustively. This means that the extent to which the alternatives are adequately explored depends on the range of options that come to mind for a human designer or analyst. This challenge is particularly daunting when considering how to achieve coordinated, coherent unit outcomes in distributed, network-centric operations. How do we devise new tactics for a group of distributed, autonomous agents? More specifically, how can we explore the tactical possibilities for employing swarming entities? Recent advances in machine learning techniques make it possible to consider building

tools to help automate some aspects of this discovery and evaluation process. We are exploring this possibility by developing and demonstrating a new technology for learning tactics and behaviors automatically from experience in a simulation. The initial focus of our research has been on learning distributed building behaviors (e.g., nest-building by a group of simulated wasps). Subsequent investigations will examine how learning techniques can be used to generate behaviors for a group of simulated micro-air vehicles conducting simple reconnaissance and surveillance tasks.



For more information, contact Dr. Lashon Booker, [booker@mitre.org](mailto:booker@mitre.org), 703-983-7609.

## Highlights of the next issue of Collaborations ...

### WHAT'S NEXT?

In our next issue, we will look at what's happening in Software Engineering. MITRE's software-intensive systems are heavily dependent on software engineering. It is often difficult to separate systems engineering from software engineering activities. The success of a system development depends on doing both well. We will look at what innovations are happening in software engineering and what has been their impact on the quality of software and on productivity of software developers.

### WHAT DO YOU THINK?

We welcome feedback from our readers. Do you agree or disagree with what is in the newsletter? Do you have information you would like to add? We want to publish your responses to share with our other readers. Send email to [sepo@mitre.org](mailto:sepo@mitre.org) with your suggestions.

# Social Science Research on Complex Systems

Complex systems engineering poses many challenges for the people who define the operational requirements, design the systems, carry out acquisition, and use them. These problems arise from the diversity of stakeholders, the need for collaboration among them, and the necessity for change by all of them. Social science research can contribute to these aspects of engineering for complex systems by understanding how individuals and groups interact with each other and with the technology.

In engineering enterprise systems, for example, the challenges for social science research include how do various stakeholders reach a consensus on system requirements; how can policy makers understand and facilitate new rules for system behavior and for system acquisition; how can users be encouraged to change their business rules and their organizations; how can systems engineers understand the complexity of a system, including its cause and effect relationships; and how can they work with each other to incorporate multiple views and multiple technologies. Additionally, there are a range of issues around how system operators from different organizations distributed across an enterprise learn to share information and collaborate in their decision making, as well as how they adapt to changes in the system as it adapts to them and to its environment. Relevant areas of social science research include collaboration and team building, cognitive science, training, social decision making, negotiation, organizational change, and ethnographic studies. Applying the results of such social science research to the challenges identified above can support effective adoption of a complex enterprise system by the people who must use it.



For more information on social science research about complex systems, contact Dr. Jo Ann Brooks, [jbrooks@mitre.org](mailto:jbrooks@mitre.org), 781-271-5330; or LeeEllen Friedland, [lfriedland@mitre.org](mailto:lfriedland@mitre.org), 703-983-7809.



## Who We Are

The MITRE Systems Engineering Process Office (SEPO) is a nexus for systems engineering information and activity at MITRE. Our team brings together useful systems engineering resources, provides guidance on systems engineering processes, and participates in systems engineering activities throughout The MITRE Corporation.

Systems engineering resources are available through the SEPO Library, which contains a broad spectrum of information and knowledge to help you on such topics as acquisition, systems engineering, software engineering, decision support, and process management.

Systems engineering expertise is available through the SEPO Technical HOTline. Emails sent to the HOTline reach multiple subject matter experts, who can provide answers to your questions, connections to other experts on the subject here at MITRE, or contact with other people who are working on the same problem.

We offer systems engineering guidance through our SEPO Toolkits. Toolkits are available online or on CD and include many topics on the system engineering process. For guidance in another area, such as Software Engineering, Acquisition, the Capability Maturity Model - Integrated (CMMI) Process, or sponsor-specific systems engineering areas, please contact our team.

Collaborations is a publication of SEPO. For additional information, please contact:

Brian E. White, Ph.D., SEPO Director  
781-271-8218; Email: [SEPO@mitre.org](mailto:SEPO@mitre.org)

This newsletter is a publication of the Systems Engineering Process Office (SEPO). Additional copies are available.

The MITRE Corporation, 202 Burlington Road, Bedford, MA 01730-1420, and 7515 Colshire Drive, McLean, VA 22102-7508  
[www.mitre.org/work/sepo/](http://www.mitre.org/work/sepo/)

©The MITRE Corporation, 2004

Approved for Public Release;  
Distribution Unlimited.  
Case Number 04-1067