MODELING OF COMPLEX SYSTEMS

The Modeling of Complex Systems Program is a program of fundamental mathematics-oriented research the objectives of which are to

Develop quantitative models of complex phenomena of interest to the Army, especially those for which current models are not based on first/basic principles

Develop new metrics, preferably those based on first/basic principles, for these models.

The complex phenomena of interest to the Modeling of Complex Systems Program include 1) physical phenomena, 2) abstract phenomena in information theory and networks and 3) behavioral phenomena. Complete and consistent mathematical frameworks for the modeling effort are the preferred context for the research, but research that does not take place in such frameworks can be considered if the phenomena are so complex that the frameworks are not feasible. Metrics are part of the mathematical framework and are of great interest. Traditional metrics, when they exist, often do not measure the characteristics in which observers in general and the Army in particular are interested. For many complex phenomena, new metrics need to be developed at the same time as new models. Just as is the case for the modeling effort, these metrics should preferably be in a complete mathematical framework.

The research in modeling of and metrics for complex phenomena of interest to the Modeling of Complex Systems Program may include numerical/computational work as a subordinate component. However, research that focuses mainly on numerical/computational issues should be directed to the ARO Computational Mathematics Program in the ARO Mathematics Division.

The investment in the Modeling of Complex Systems Program is in the following areas

AA-1: Advanced Complex Materials for Structures, Armor and Sensors
AA-2: Inverse Scattering in Complex Media
AA-3: Modeling of Multiscale Objects and Functions
AA-4: Nonlinear Dynamics for Communication
AA-5: Data Fusion in Complex Networks
AA-6: Dynamics of Distributed Networks of Embedded Sensors and Actuators
AA-7: Additional Areas of Opportunity

The Modeling of Complex Systems Program seeks to have a balance between research for “hard” (physics-based) areas and “soft” (information and behavioral-based) areas.

Thrust AA-1: Advanced Complex Materials for Structures, Armor and Sensors

The analysis, design and manufacture of advanced materials is an interdisciplinary area in which the basic principles are often known. However, the current models for meso and macro behavior of materials are often not based on these principles because implementation of the basic principles in the models results in inordinate complexity and because principles on intermediate levels are not well known. The Modeling of Complex Systems Program supports research oriented toward optimizing properties or performance characteristics of highly nonlinear materials, including advanced composites for structures and armor and smart materials for sensors.

Light-weight, high-strength structural components, including advanced composites, contribute to attaining mobility and protection requirements for U.S. forces (as well as to the fuel efficiency and safety of the U.S. automobile fleet). Advanced composites are challenging to analyze and design because of the presence of many interacting length scales. Smart materials, the functional ingredients of actuators, sensors and transducers, that have a load- or field-dependent (crystal or other) structure. Such materials may undergo a phase transformation when some mechanical, thermal, electrical or magnetic factor changes and vice versa. Advanced composites and smart materials are typically highly nonlinear. In seeking to understand the relationship between the microscopic and macroscopic length scales of these materials, fundamental issues in nonlinear modeling arise. The program invests in research on these fundamental issues, including development of basic equations and constitutive laws.

Thrust AA-2: Inverse Scattering in Complex Media

Inverse scattering is of interest to the Army for detection and identification of landmines and unexploded ordnance with low false alarm rates. This is an area involving the interaction between the propagation of various types of waves in cluttered soils and the inverse problem of detecting location, shape and material properties of solid objects having various waveform signatures. Currently available techniques often have high false alarm rates, which impedes mine clearance. Additional Army interests include electromagnetic sensing through cluttered battlefield atmospheres, including smoke, fog, flames, etc. Application of inverse scattering techniques for stand-off detection of chemical and biological agents is of interest.

One of the directions of research supported by the Program is that of creating models for currently unused sources of information, validating these models and integrating them into larger models or systems. Traditionally, imaging by ground-penetrating radar and by x-rays has utilized information only from singly scattered waves, that is, waves that are scattered by a collision with only one object and then return to the detectors. For such imaging, multiply scattered waves that arrive at the detectors create error, because they are erroneously presumed to have resulted from a single scattering event. However, multiply scattered waves contain information, not just error. Creating models that are able to access the information in multiply scattered waves is of considerable interest to the Program. Integrating these models into models/systems that also use the information in singly scattered waves is of interest. The interests of the Program in research on multiple scattering in complex media include research on models for utilizing other sources of information that are ignored by current models.

Thrust AA-3: Modeling of Multiscale Objects and Functions

Representation of complex, multiscale/mulitresolution geometric objects and of complicated, often high-dimensional abstract phenomena and functions is fundamental for Army, DoD and civilian needs in modeling of terrain, geophysical features, biological objects (including humans and their clothing), computational learning and many other objects and functions. Real-time visualization of huge terrain databases with glitch-free zoom-in/out cannot be achieved with current techniques. Progress in automatic target recognition, robotic vision, representation/compression of data in general and many other areas depends on advances in approximation theory. A key to achieving these goals is data compression at ratios and with accuracy that exceed what is currently known.

A multitude of variants of piecewise planar surfaces (including those on triangulated irregular networks or “TINs”), splines , multiquadrics, kriging, wavelets, neural nets and many other techniques developed in the past perform well on many types of data. However, none of these procedures are able to provide, without human intervention, representation of geometry and data with the accuracy and compression that is needed. To achieve such representation, new types of approximation theory appropriate for complicated multiscale/multiresolution surfaces and phenomena need to be developed. In these cases, the objects/functions being approximated are not consistent with the assumptions of classical approximation theory. Approximation theory research that results in highly compressed, loss-free or minimally lossy representation is of particular interest. Approximation theory for information flow and other abstract items in large communication and computer networks is an area of interest.

The approximation theory developed under support of this program is expected to provide building blocks for computational geometry, pattern recognition, automatic target recognition and visualization systems. However, research that is focused on these areas rather than on approximation theory is beyond the scope of the Modeling of Complex Systems Program and fits best with the Image Fusion, Processing and Circuits Program of the ARO Computing and Information Sciences Division and with the Discrete Mathematics and Computer Science Program of the ARO Mathematics Division.

Thrust AA-4: Nonlinear Dynamics for Communication

Enhanced capability in digital communication is recognized as a pivotal element in a modern economy and in national security. At present, digital communication is carried out mainly by linear devices, that is, by transmitters and receivers operating in the so-called linear regime. The option of creating digital communication systems based on transmitters and receivers operating in the nonlinear regime is already under investigation. One type of nonlinear behavior on which these transmitters, receivers and codes can be based is chaos, that is, the deterministic but complicated behavior of physical systems in which arbitrarily small changes in the input produce large changes in the output. The potential advantages of nonlinear digital communication devices include increased power and bandwidth efficiency, light weight, compactness, increased information-bearing capacity, greater number of channels, low-cost manufacturing, low probability of interception (LPI) and low probability of detection (LPD).

The Modeling of Complex Systems Program is interested in the nonlinear modeling that needs to be done to create new, nonlinear transmitters, receivers and codes. Research in controlling chaos, which is inherently unstable, is ways suitable for these devices and codes is important. Investigation of the information theoretic and symbolic dynamic properties of the signals produced (for example, size of alphabets, grammatical constraints on symbol sequences and entropies) is of interest. This research should be carried out in the context that leads to simple, inherently nonlinear devices. However, the engineering design of such devices is outside the scope of the Modeling of Complex Systems Program and fits best with an appropriate program in the ARO Electronics Division. Soliton theory for fiber optics communication is an important area of research but is beyond the scope of the Modeling of Complex Systems Program.

Thrust AA-5: Data Fusion in Complex Networks

Enhanced capability in distributed sensing by organized or self-organizing networks of large numbers of geographically dispersed sensors, often microsensors (acoustic, infrared, magnetic, etc.), of various modalities is increasingly recognized as a pivotal element in the ability of defense forces to accomplish their mission. Such networks are a potential replacement for landmine fields

Over the past generation, great progress has been made in research and development of low-cost sensing devices. When networks contain small numbers of sensing devices, issues of network organization and topology and issues of information processing can often be addressed in known scientific/engineering frameworks. However, when networks contain large numbers of sensing devices, issues of information flow and information processing are a challenge for which basic principles remain to be created. Such basic questions as how to measure “goodness” or optimality are still open. As the number of devices in distributed sensing systems increases from hundreds to thousands and perhaps millions, the amount of attention paid to information flow and processing must increase sharply.

The Modeling of Complex Systems Program is interested in research on information flow and information processing in large, dynamic networks of sensors, primarily microsensors with limited capabilities and power. Development of metrics, preferably based on first principles rather than ad hoc, for measuring goodness is a topic of concern. Developing models (more likely nonlinear than linear) for linkage of scales in the information processing system for large networks is of interest. Research that leads to improved information processing under strong constraints on power and communication bandwidth is of particular interest.

Thrust AA-6: Dynamics of Distributed Networks of Embedded Sensors and Actuators

The past twenty years has seen the convergence of communication and computation. This period has also seen the proliferation of embedded integrated-circuit devices, the growth rate of which has been higher than that of personal computers. Low-cost wireless networking, which is now becoming common, may be the catalyst that will lead to networking of embedded devices in Army and DoD sensing and weapons platforms, vehicles, soldiers and command and control organizations. The analysis and design of networks of embedded sensors and actuators will involve modeling at much deeper levels than that of bit flow. This design and analysis requires a solid mathematical foundation focused on issues of stability, robustness and performance not merely of the sensors and actuators but also of the people and objects in which they are embedded.

Thrust AA-7: Additional Areas of Opportunity

Behavioral modeling is an area of nonlinear modeling for which few basic principles are currently known. Research in this area is critical for military and civilian decision making, training and rehearsal and is an area of potential investment of the Modeling of Complex Systems Program.

Commercial speech-recognition research and products have focused on environments with low noise and clutter and have not handled situations with signal-to-noise ratios of -10dB and lower that are typical for tanks, helicopters and battlefield situations in general. Speech recognition in high-noise, high-clutter environments are important for improved, hands-off human-computer interaction of military personnel and are of potential interest to the Program. An exciting area of new research in speech recognition is nonlinear partial differential equation models based on the human auditory system that may provide a key to speech recognition at very low signal-to-noise ratios. This research may involve inverse-problem techniques generically related to Thrust AA-2 and approximation theory research related to Thrust AA-3.

The nonlinear modeling of information flow and other abstract issues in large communication and computer networks is of interest. Approximation theory research mentioned above under Thrust AA-3 may be a component of this modeling. Modeling information flow and other dynamics in large networks is important research that is required for information assurance, that is, for protecting networks from unforeseen catastrophes and from deliberate attack.

Analytical procedures that provide new ways to “image” networks, such as “network tomography” (deduction of network topology or other properties from measurements at a relatively small number of nodes or locations) are of interest.

Cooperation with the new Information Assurance Program in the ARO Computing and Information Sciences Division is envisioned. Some of this work may overlap with nonlinear modeling of networks mentioned under Thrust AA-4 above.

The interests of the Modeling of Complex Systems Program are not limited to the areas listed above but include mathematics-oriented research for other complex phenomena of interest to the Army for which models based on first/basic principles are not yet available.