Toward Self-Healing Infrastructure Systems

A joint industry-government initiative is developing a mathematical basis and practical tools for improving the security, performance, reliability, and robustness of energy, financial, telecommunications, and transportation networks. The first challenges are to develop appropriate models for this degree of complexity and create tools that let components adaptively reconfigure the network as needed.

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Virtually every crucial economic and social function depends on the secure, reliable operation of energy, telecommunications, transportation, financial, and other infrastructures. Indeed, these infrastructures have provided much of the good life that the more developed countries enjoy. However, with increased benefit has come increased risk. As they have grown more complex to handle a variety of demands, these infrastructures have become more interdependent. The Internet, computer networks, and our digital economy have increased the demand for reliable and disturbance-free electricity; banking and finance depend on the robustness of electric power, cable, and wireless telecommunications. Transportation systems, including military and commercial aircraft, land vehicles, and sea vessels, depend on communication and energy networks. Links between the power grid and telecommunications and between electrical power and oil, water, and gas pipelines continue to be a linchpin of energy supply networks.

This strong interdependence means that an action in one part of one infrastructure network can rapidly create global effects by cascading throughout the same network and even into other networks. The potential for widespread disturbances is much higher, as the "The Cost of Cascading Failure" sidebar describes. Moreover, interdependence is only one of several characteristics that challenge the control and reliable operation of these networks. These characteristics, in turn, present unique challenges in modeling, prediction, simulation, cause-and-effect relationships, analysis, optimization, and control. What set of theories can capture a mix of dynamic, interactive, and often nonlinear entities with unscheduled discontinuities? Deregulation and economic factors and policies and human performance also affect these networks.

The Complex Interactive Networks/Systems Initiative (CIN/SI), a joint Electric Power Research Institute-US Department of Defense program, is addressing many of these issues. The goal of the five-year, $30 million effort, which is part of the Government-Industry Collaborative University Research program, is to develop new tools and techniques that will enable large national infrastructures to self-heal in response to threats, material failures, and other destabilizers.[1,2] Of particular interest is how to model enterprises at the appropriate level of complexity in critical infrastructure systems.

Part of CIN/SI's work, which began in spring 1999 and involves 28 universities, draws from ideas in statistical physics, complex adaptive systems (CAS), discrete-event dynamical systems, and hybrid, layered networks. CAS researchers view the complex system as a collection of individual intelligent agents that adapt to events and surroundings, acting both competitively and cooperatively for the good of the entire system. By simulating agent-based models, stakeholders can better grasp the true dynamics of complex intercomponent and intersystem actions. As models become progressively more realistic, designers can map each system component to an adaptive agent. The adaptive agents would then manage the system using multilevel distributed control.[3-5] Through its environmental sensor, each agent would receive continuous messages from other agents. If agents sense any anomalies in their surroundings, they can work together, essentially reconfiguring the system, to keep the problem local. Thus, the agents would prevent the cascad-

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ing effect—the main source of vulnerability in critical infrastructure systems.

CHARACTERIZING COMPLEXITY

Infrastructure networks have several common characteristics that make them difficult to control and operate reliably and efficiently:

- Billions of distributed heterogeneous components are tightly interconnected. The scale is massive. For example, the time scale can range from milliseconds for one task to hours and even years for another; spatial scales can span a city or a continent.
- Attacks and disturbances can lead to widespread failure almost instantaneously.
- A variety of participants—owners, operators, sellers, buyers, customers, data and information providers and users—interact at many points.
- The number of possible interactions increases dramatically as participants are added. No single centralized entity can evaluate, monitor, and manage all the interactions in real time.
- The relationships and interdependencies are too complex for conventional mathematical theories and control methods. Infrastructures that interact with their users and other networks (for example, an automatic switching system for tele-

The Cost of Cascading Failure

In most critical infrastructure networks, systems are spread across vast distances, are nonlinear, and are highly interactive. In any situation subject to rapid changes—from natural disasters, purposeful attack, or unusually high demands—completely centralized control requires multiple, high-data-rate, two-way communication links, a powerful central computing facility, and an elaborate operations control center. But centralized control may not be practical in this setting because a failure in one part of the network can spread unpredictably almost instantaneously—including to the centralized control elements. Thus, centralized control is likely to suffer from the very problem it is supposed to fix.

A pertinent question is how to manage and robustly operate these systems that have hierarchical layers and are distributed at each layer. An alternative strategy is to have some way to intervene locally (where the disturbance originates) and stop problems from propagating through the network. Some researchers have shown[1] that dropping (shedding) approximately 0.4 percent of the total network load for 30 minutes would have prevented the cascading effects of the July-August 1996 blackout (described later), which ended up costing $1.5 billion and included all aspects of interconnected infrastructures and even the environment.

Past disturbances in both the power grid and telecommunications infrastructure provide some idea of how cascading failures work. In some cases, the local disturbance affected geographically distant areas. In others, a failure in one infrastructure led to breakdowns in other infrastructures.

In the power grid

According to data from the North American Electric Reliability Council (NERC), outages from 1984 to the present affect nearly 700,000 customers annually, or 7 million per decade. Many of the outages were exacerbated by cascading effects. Perhaps the most famous recent example is the July-August 1996 blackout in the western US grid, where on 10 August 1996, the following sequence occurred:

Faults in Oregon at the Keeler-Allston 500 kV line and the Ross-Lexington 230 kV line resulted in excess load, which led to the tripping of generators at McNary Dam, causing 500 MW oscillations, which led to the separation of the North-South Pacific Inter-tie near the California-Oregon border, which led to islanding and blackouts in 11 US states and two Canadian provinces.

In the telecommunications network

In May 1998, the Galaxy-IV satellite was disabled, triggering what *Newsweek* dubbed "The Day the Beepers Died." Because the Galaxy-IV is equipped with the latest technology, most paging companies use it. The failure affected 40 million pagers, National Public Radio went off the air, airline flights were delayed, and data networks had to be manually switched to older satellites. PageNet, the largest US pager provider, has about 3,000 satellite dishes, and it had to manually realign every dish. Each realignment took one to two hours.

Space debris is another source of telecommunications disturbance. Already, 10 million pieces of debris larger than 1 millimeter in diameter surround the Earth. Most space debris gradually drifts into the atmosphere and burns up during reentry. However, space agencies have become increasingly concerned after flecks of paint traveling at more than 13 km per second damaged both the Mir Space Station and the US Space Shuttle. Last year, space debris completely disabled a French spy satellite.

The danger of collisions is particularly acute for satellites orbiting at an altitude of 800-1400 km—where mobile phone companies are expected to launch hundreds of small satellites in the next few years. Computer simulations at the CNUCE Institute in Pisa (http://www.cnuce.pi.cnr.it) indicate that a large part of the network could self-destruct if just one satellite is hit. According to CNUCE researchers, there is also a 10 percent chance that debris will destroy one of the Iridium satellites within a decade. If one satellite is destroyed, there is a 10 percent probability that the network will fail within five years. Such a chain reaction could make the entire low-earth orbit unsuitable for satellites within 100 years.

Reference

1. N. Grudinin and I. Roytelman, "Heading Off Emergencies in Large Electric Grids," *IEEE Spectrum*, Apr. 1997, pp. 43-47.

Table 1. Actions and operations within the power grid. The time scale varies from microseconds to years, which greatly complicates modeling, analysis, simulation, control, and operations tasks.

Action or operation	Timeframe
Wave effects (fast dynamics, such as lightning causing surges or overvoltages)	Microseconds to milliseconds
Switching overvoltages	Milliseconds
Fault protection	100 milliseconds or a few cycles
Electromagnetic effects in machine windings	Milliseconds to seconds
Stability	60 cycles or 1 second
Stability augmentation	Seconds
Electromechanical effects of oscillations in motors and generators	Milliseconds to minutes
Tie line load frequency control	1 to 10 seconds; ongoing
Economic load dispatch	10 seconds to 1 hour; ongoing
Thermodynamic changes from boiler control action (slow dynamics)	Seconds to hours
System structure monitoring (what is energized and what is not)	Steady state; ongoing
System state measurement and estimation	Steady state; ongoing
System security monitoring	Steady state; ongoing
Load management, load forecasting, generation scheduling	1 hour to 1 day or more; ongoing
Maintenance scheduling	Months to 1 year; ongoing
Expansion planning	Years; ongoing
Power plant site selection, design, construction, environmental impact, and so on	10 years or longer

phone calls) create additional complexity because the interaction of their elements further increases the number of possible outcomes.

In addition to these shared characteristics, each infrastructure has specific objectives that pose formidable challenges. To get an idea of the complexity involved, it helps to understand some of the issues facing the power grid, which underlies almost every other infrastructure, and the telecommunications and transportation networks, which are vital to almost every aspect of daily living.

The power grid

The North American power grid evolved over the past 100 years without a conscious awareness of how its evolution would affect its operation under deregulation, the digital economy, and interaction with other infrastructures. Widespread outages and huge price spikes during the past four years have raised public concern about grid reliability at the national level. The potential for larger scale and more frequent power disruptions is considered higher now than at any time since the great Northeast blackout in 1965. The ramifications of network failure have never been greater, as the transportation, telecommunications, oil and gas, banking and finance, and other infrastructures depend more and more on the power grid to energize and control their operations.

The power grid is a sprawling network with many operational levels involving a range of energy sources (nuclear, fossil fuel, and renewable resources) with many interaction points (operators, power consumers and producers, and several layers including power plants, control centers, and transmission, distribution, and corporate networks). Because of competition and deregulation in recent years, multiple producers now share the delivery network. Demand is already outpacing available resources in several regions: During the past decade, actual demand increased some 35 percent; capacity increased only 18 percent because it is becoming increasingly harder for power generators and delivery entities to get permits and ensure that their return on investment is acceptable. Thus, the complex systems that relieve bottlenecks and clear disturbances during peak demand are now closer to the edge and at greater risk of serious disruption.

Another contributor to complexity is that digital users require a much higher quality of electricity. Some experts indicate that reliability will need to go from 99.9 percent (roughly eight hours of power loss per year) to 99.99999999 percent reliability (32 seconds of power loss per year). The industry will also need new equipment to protect against sags and disruptions.

Finally, the time and operational scales at which the infrastructure operates are an important part of complexity. As Table 1 shows, the time scale for various power grid control and operation tasks can be anywhere from microseconds to a decade.

Telecommunications

The globalization of our economy is built on telecommunications networks, including fixed (public switched telephone and data networks), wireless (cellular, PCS, wireless ATM), and computer (the Internet and millions of computers in private and public use) networks—and these networks are growing rapidly. Fixed communications networks require secure, reliable, high-quality power supplies.

The telecommunications infrastructure, like the power grid, is becoming overburdened. The satellite network, just one segment of this infrastructure, is a good example. According to Via Satellite, an online telecommunications industry publication, 13 geostationary communications satellites were launched in the 1960s, 35 in the 1970s, 69 in the 1980s, and 130 from 1990 to 1996. Approximately 120 additional communications satellites are scheduled for launch before the end of 2000. The number of satellite operators rose from two in the 1960s to 50 in 1996, and is expected to reach 60 by the end of this year. These numbers exclude most Russian- and Chinese-built satellites. NASA reports that more than 3,500 satellites now orbit the earth, relaying enormous amounts of voice and data traffic.[6]

The satellite network has three main layers:

- low-earth orbit, 200 to 2,000 km (“little LEOs” at 750-1500 km), operating at VHF, UHF below 500MHz; low complexity;
- medium-earth orbit, 2000 to 20,000 km (big LEOs/MEOs at 750-11,000 km) operating at L and S microwave (1.6 and 2.5 GHz) with high to very high complexity; and
- geosynchronous orbit (GEO), at 36,000 km, operating at K microwave (19 and 29 GHz), with variable low to high complexity.

Some of the most familiar services are detailed Earth imaging, remote monitoring of dispersed locations, and highly accurate location and tracking using the continuous signals of the global positioning system (GPS). Satellite-based business and personal voice and data services are now available throughout much of the world.

The terrestrial fiber, local microwave, and digital cable networks that telephone and cable companies are currently expanding and upgrading will carry much of the broadband communications. Some 170 non-military satellites, 3,600 transponders, and 80 spacecraft are in service or planned for deployment. More than 2,200 new transponders are expected in the next five years, with 15- to 25-year lifetimes. The consulting firm Booz-Allen and Hamilton forecasts that the global market for broadband communications will grow to nearly $200 billion by 2005 and that space-based systems will capture 10 to 15 percent of that market.

The Internet is rapidly expanding the range of applications for satellite-based data communications; two of the most popular applications are accessing the Internet itself and connecting remote sites to corporate networks. Some satellite systems, including those of satellite TV providers, let users browse Web pages and download data—at 400 kbps—through a 21-inch (53 cm) roof-mounted dish receiver connected to a personal computer with an interface card. This capability could become a valuable tool for expanding an enterprise network to remote offices around the world.

Some utilities are diversifying their businesses by investing in telecommunications and creating innovative communications networks that cope with industry trends toward distributed resources, two-way customer communications, and business expansion, as well as addressing the measurement of complex and data-intensive energy systems via wide-area monitoring and control. Figure 1 shows a possible scenario. Challenges include how to handle network disruptions and delays and manage orbits from the satellite. A big source of complexity is the interdependence of the telecommunication networks and the power grid.

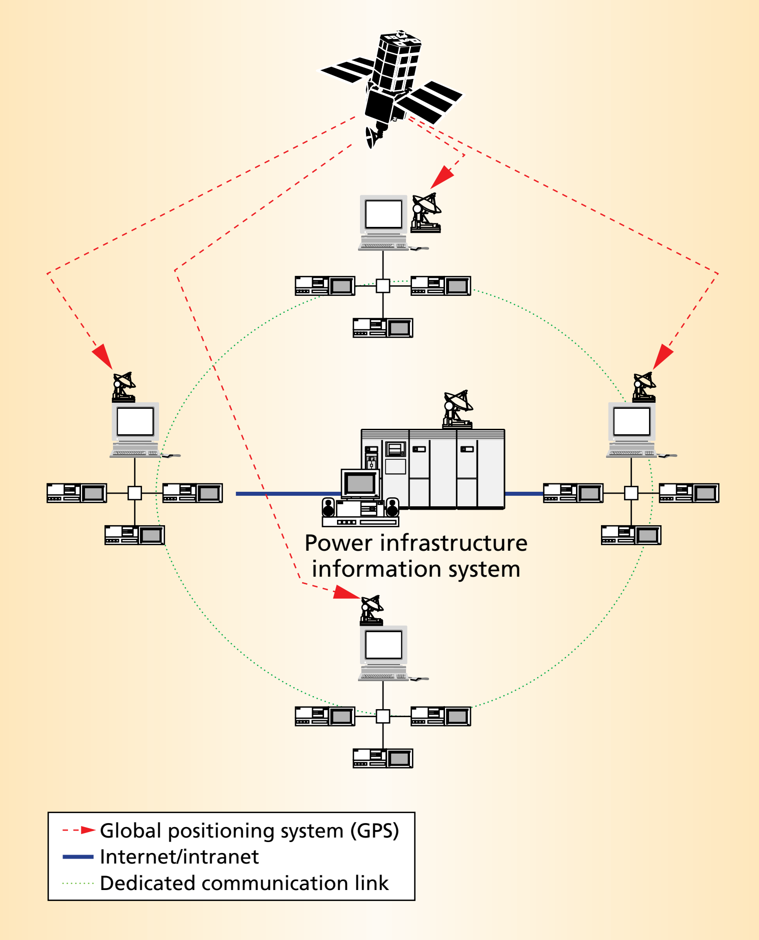

Figure 1. How the telecommunications network and the electric power grid are becoming increasingly interdependent. Issues range from the highest command and control level (the power infrastructure information system) to the individual power stations and substations at the middle level, and then to the devices and power equipment at the lowest level. The Internet/intranet (solid blue line) connecting the middle-level stations is an Ethernet or model-based network with individual gateways. The dedicated communications link (green dotted line) is a fiber-optic cable or microwave system. The global positioning system (dashed red arrows) handles time synchronization. In this scenario, satellite technology is used for a range of utility and business applications including direct-to-home interactive services and wide-area monitoring and control. (Image courtesy of Prof. C-C. Liu of the University of Washington.)

Transportation

The backbone of the US transportation system and economy is the road infrastructure. This system has continually evolved since the 1930s, and the cost to build and maintain it is rising. The US Department of Transportation estimates that the annual cost of congestion in lost productivity alone is more than $100 billion. In addition, more than 40,000 persons are killed and another 5 million injured each year in traffic accidents.

Where feasible, increasing the number of lanes or building new roads can expand present capacity, but in some areas adding roads can’t meet the demand (both from population growth and travel). A less expensive and disruptive solution is to intelligently manage the existing road infrastructure. The idea is to create and deploy technologies to improve the safety, capacity, and operational efficiency of the surface transportation system, while simultaneously reducing the burden on the environment and on energy sources.

With these objectives in mind, Congress launched the US Intelligent Transportation Systems (ITS) program in 1991. One of the program's goals is to develop Advanced Traffic Management Systems. ATMS will rely on the consolidation of information, automotive, and highway technology. A wide range of small, complementary systems—from electronic route guidance to preemptive signal control—will essentially automate highways. Sensors and communication devices will be along the roads, as well as in the vehicles. Thus, the road will "know" its operational status, which it will then communicate to the vehicle. The vehicle operator can then make informed decisions about which routes to take to optimize individual trips and daily travel plans. Entities such as traveler information services and fleet management can use the data to plan, implement, and manage their daily operations.

The idea is to create and deploy technologies to improve the safety, capacity, and operational efficiency of the surface transportation system.

Public and private concerns can also use ATMS in their daily operations, including public and rural transportation management, priority vehicle management, and freight and fleet management. Thus, although it poses great analytical challenges, the ATMS thrust offers significant payoff because of its broad geographical coverage and direct impact on regional economies.[7,8]

As complex as it is, the road system is only one segment of the transportation network. The demand for air, land, and sea transportation and distribution networks is growing. As in the other infrastructures, there are diverse sources of complexity and interdependence. Rail networks, for example, are becoming increasingly dependent on electricity (electric and magnetic levitation trains); transportation is linking with sensors, telecommunications, and satellites; and interest in traffic modeling, prediction, and management is increasing.

AGENT TECHNOLOGY

As these overviews show, infrastructures are highly interconnected and interactive, making them well-suited for agent technology. Indeed, infrastructure networks already use agents in the form of decision-making and control units distributed among layers throughout physical, financial, and operational subsystems (including supervision, maintenance, and management). Agents assess the situation on the basis of measurements from sensing devices and information from other entities. They influence network behavior through commands to actuating devices and other entities. The agents range in sophistication from simple threshold detectors (that choose from a few actions on the basis of a single measurement) to highly intelligent systems.

The US power grid has thousands of such agents, and power system dynamics are extremely complex. Actions can take place in microseconds (such as a lightning strike), and the network's ability to communicate data globally is limited. For these reasons, no one can preprogram the agents with the best responses for all possible situations. Thus, each agent must make real-time decisions from local, rather than global, state information. Many agents (particularly, controllers for individual devices) are designed with relatively simple decision rules based on response thresholds that are expected to give the most appropriate responses to a collection of situations generated in off-line studies.

Context-dependent agents

This approach does not offer sufficient reliability, however. Power grid agents have been known to take actions that drive the system into undesirable operating states. In some cases, the agents acted as programmed, but the predesigned actions were not the best responses to the actual situation—the context. In many cases, the agent could have been made aware of the context, and thus would have known that the preprogrammed action was not appropriate.

Context dependence is a key difference between agents as they are currently designed and the adaptive agents that CIN/SI researchers are developing. In a context-dependent agent-based network, agents cooperate and compete with each other in their local operations while simultaneously pursuing the global goals set by a minimal supervisory function. In the power grid, for example, a network of local controllers would act as a parallel, distributed computer, communicating via microwaves, optical cables, or the power lines themselves, and intelligently limit their messages to information needed to optimize the entire grid and recover from a failure. Thus, in essence, the components become context-dependent intelligent robots that cooperate to ensure successful overall operation and act independently to ensure adequate individual performance.

Agent evolution

The agents evolve, gradually adapting to their changing environment and improving their performance even as conditions change. A single bus would strive to stay within its voltage and power flow limits while still operating in the context of the voltages and flows that power system managers and other agents impose on it. Advanced sensors, actuators, and microprocessors would be associated with generators, transformers, buses, and so on. Modelers use object-oriented methods and object hierarchies of simpler components to model more complex components,

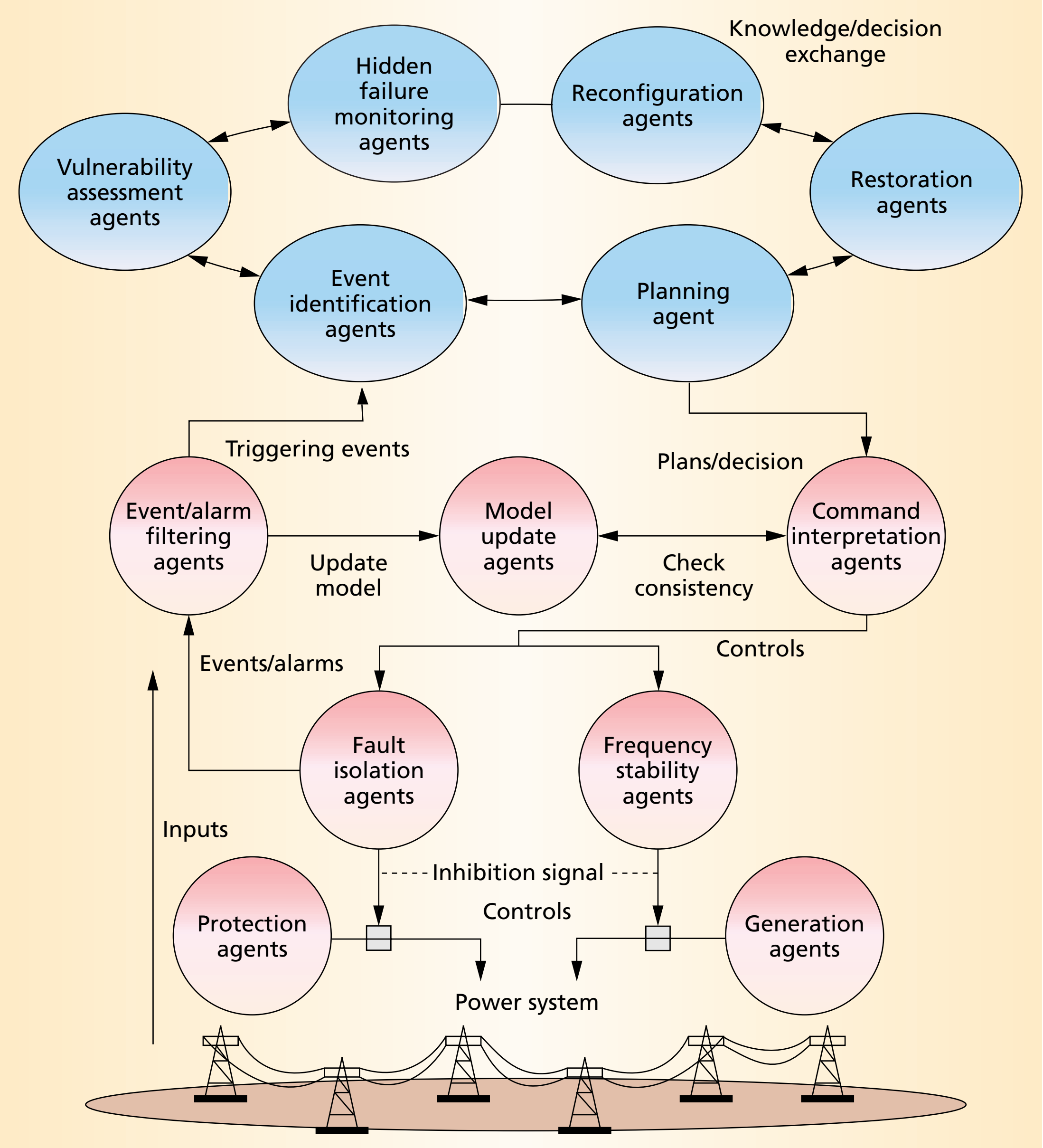

Figure 2. A multiagent system design. This design organizes agents in three layers: The reactive layer (bottom) consists of agents that perform preprogrammed self-healing actions that require an immediate response. Reactive agents, whose goal is autonomous, fast control, are in every local subsystem. The agents in the coordination layer (middle) include heuristic knowledge to identify which triggering event from the reactive layer is urgent, important, or resource consuming. These agents, whose goal is consistency, also update the system's real-world model and check if the plans (or commands) from the deliberative layer (top) represent the system's current status. If the plans don't match the real-world model, the agents in the middle layer trigger the deliberative layer to modify the plans. The deliberative layer consists of cognitive agents that have goals and explicit plans that let them achieve their goals. The goals of agents in this layer are dependability, robustness, and self-healing.

such as a generating plant or a substation, thus creating a hierarchy of adaptive agents.[1,3,5]

So that it is aware of context and can evolve, each agent and subagent, which is represented as an autonomous active object, is equipped with appropriate algorithms (intelligence). Evolution is enabled through a combination of genetic algorithms and genetic programming. Classes are treated as an analogy of biological genotypes, and objects are instantiated from them as an analogy of their phenotypes. When instantiating objects to form individual agents, operations typical of genetic algorithms, such as crossover and mutation, can select and recombine their class attributes, which define all the potential characteristics, capabilities, limitations, or strategies these agents might possess.

The physics specific to each component will determine the object-agent's allowable strategies and behaviors. Researchers can augment existing instrumentation and control capabilities and run computer experiments with hypothetical, optional capabilities to evaluate their benefit.

Research in the Six CIN/SI Consortia

The objective of the Complex Interactive Networks/Systems Initiative (CIN/SI) is to significantly and strategically advance the robustness, reliability, and efficiency of the interdependent energy, communications, financial, and transportation infrastructures. Part of that work must determine if there is a unifying paradigm for simulating, analyzing, and optimizing time-critical operations. CIN/SI, a five-year initiative that began in spring 1999, has funded six consortia, with participation from the Tennessee Valley Authority and Commonwealth Edison Co., which are providing real-world power grid data, staff expertise, and test and demonstration sites for new modeling, measurement, control, and management tools.

An EPRI report, "Complex Interactive Networks/Systems Initiative: First Annual Report: Overview and Progress Report for Joint EPRI and US Department of Defense University Research Initiative" (TP-114660), and reports from the six consortia (TP-114661–114666) are available at http://www.epri.com or by calling EPRI at +1 800 313 3774.

From Power Grids to Power Laws: A Mathematical Foundation for Complex Interactive Networks

Cal Tech (lead); MIT; University of California, Los Angeles; University of California, Santa Barbara; and University of Illinois, Urbana-Champaign

The focus is on systems optimized to be robust despite uncertain environments. Power laws in these systems are due to trade-offs between resource yield and cost and risk tolerance. These trade-offs lead to highly optimized designs that allow for occasional large events (such as large grid outages). One effort aims to combine and integrate the model reduction of large-scale systems. Another aims to use theoretic tools to control Internet congestion. The objective is to bring more rigorously grounded principles to study data network flow-control mechanisms.

Context-Dependent Network Agents

Carnegie Mellon (lead), RPI, Texas A&M, University of Minnesota, and University of Illinois

Current design practices in power system networks (and other dynamic networks) do not fully exploit memory, computing, and communication technology. The objective of this consortium is to develop appropriate algorithms (intelligence) for use in designing and deploying online context-dependent network agents.

Minimizing Failures While Maintaining Efficiency of Complex Interactive Networked Systems

Cornell (lead); University of Illinois; University of California, Berkeley; George Washington University; Washington State University; and University of Wisconsin, Madison

Basic infrastructure systems are rapidly becoming more automated because of tremendous advances in information processing and networking. To be safe, secure, reliable, and survivable, these systems must be able to withstand internal and external threats and deal with both natural hazards (weather and so on) and malicious attacks. The thrust is to develop computational theories and engineering processes and tools for networked systems

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As part of research on context-dependent network agents, investigators are developing a robust dynamic real-time computing architecture that will

- ensure the robustness of the software infrastructure using an analytically redundant software architecture with two complementary components: a simple, highly reliable core component that guarantees the minimal essential services, and a complex component that provides many desirable features such as the ability to replace the control agents without the need to shut down and then restart the normal operations. The useful but noncritical complex component will extensively use commercially available software components to lower the cost. The reliable core will function in spite of failures in the complex component and will provide the network state information to restart the complex component should it fail.
- provide timely and consistent contexts for distributed agents. The stochastic events arising from the dynamics of the power network drive the coordination between distributed agents. An event-driven real-time communication architecture will assemble relevant distributed agents into task-driven teams and will provide the teams with timely and consistent information to carry out coordinated actions.

MULTIAGENT SYSTEMS

A multiagent power grid system uses two types of agents: *cognitive* (rational) and *reactive*. Each cognitive agent has a knowledge base that comprises all the data and know-how required to carry out its task and to handle interactions with the other agents and its environment. Cognitive agents are also *intentional*, in that they have goals and explicit plans that let them achieve their goals.

The reactive agent, in contrast, claims that it is not necessary for agents to be individually intelligent for the system to demonstrate intelligent behavior overall. The reactive agents work in a hard-wired stimulus-response manner. The reactive agent's goals are only implicitly represented by rules (or simple logic), so it must consider each and every situation in advance. The reactive agent's advantage lies in its ability to react fast.

As Figure 2 shows, a multiagent system has three layers. The *reactive* layer (bottom) is in every local subsystem and performs preprogrammed self-healing actions that require an immediate response. The agents in the middle layer, the *coordination* layer, include heuristic knowledge to identify which triggering event from the reactive layer is urgent, important, or resource consuming. If a triggering event exceeds a threshold value, this agent will allow the event to go to the *deliberative* layer (which contains the cognitive agents). The agents in the deliberative layer develop plans according to their virtual models, which they keep current with information from the coordination layer.

and models that maintain efficiency while reducing the likelihood of catastrophic failures. Work involves developing link-based mathematical models that capture key layered network attributes, characterizing failure mechanisms and developing predictive and prescriptive models for their mitigation, and quantifying uncertainties as they relate to network performance and reliability.

Modeling and Diagnosis Methods for Large-Scale Complex Networks
Harvard (lead); Boston University; MIT; University of Massachusetts, Amherst; and Washington University, St. Louis

The aim is to develop simulation tools (perturbation analysis and ordinal optimization) to improve robust stability and the ability to quickly detect faults. Work involves developing a set of basic tools for modeling, analyzing, and controlling complex interactive networks. Emphasis is on optimizing performance and preventing failure. Quick simulation is combined with analytical tools to address challenges in simulation modeling, analyzing abnormal behavior in interactive networks, controlling, managing, and optimizing complex networks, and data mining and early prediction of abnormal behaviors.

Intelligent Management of the Electric Power Grid through an Innovative, Anticipatory, Multiagent, High-Performance Computing Approach
Purdue (lead), University of Tennessee, Fisk University, Commonwealth Edison Co., and Tennessee Valley Authority

Analyzing the temporal characteristics of important loads suggests that we can reliably predict their behavior and thus deal with it proactively. The idea is to segment the grid into local area grids, each with a certain mix of commercial, industrial, and residential loads as well as some standby generating capacity. Within each LAG, adaptive agents are dedicated to individual loads and generators, which will be able to predict future local demand and inform the LAG about anticipated conditions. We can use anticipatory strategies for demand-side management and dispatch small generators to manage each LAG's security and integrity. The main task is to determine general criteria for defining individual LAGs and their internal agent-based operation.

Innovative Techniques for Defense against Catastrophic Failures of Complex, Interactive Power Networks
University of Washington (lead), Arizona State, Iowa State, and Virginia Tech

The vision is to create a *wide-area* intelligent, adaptive protection and control system that provides critical and extensive information in real time, assesses system vulnerability quickly, and performs timely self-healing and adaptive reconfiguration based on *systemwide* considerations. This contrasts to current narrowly focused control actions based on measurements at the substation or line level. Tasks include determining how to acquire and interpret extensive real-time information from diverse sources; how to quickly evaluate system vulnerability in a market environment with competing, self-serving agents; how to adapt performance based on systemwide assessment; how to reconfigure the power network to minimize system vulnerability; and how to develop system restoration plans to minimize disruption.

However, the virtual world model could be outdated because the agents in the deliberative layer do not always respond to the current situation.

For this reason, the agents in the coordination layer continuously compare the world models between the deliberative and reactive layers. They update the current real-world model and check if the plans (or commands) from the deliberative layer represent the system's current status. If the plans do not align with the real-world model, the agents in the coordination layer trigger the deliberative layer to modify the plans.

In addition, events from the reactive layer might contain too much detailed information for the agents in the deliberative layer. On the other hand, the plans from the deliberative layer might be too condensed for the agents in the reactive layer. There may be more than a few control signals in the reactive layer originating from the deliberative layer. The coordination layer analyzes the command and decomposes it into actual control signals. This layer might be at every local subsystem that interfaces with the reactive layer. The agents in the deliberative layer prepare higher level plans such as vulnerability assessment and self-healing.

Modeling the power industry in this control theory context is especially pertinent, since the current movement toward deregulation and competition will ultimately be limited only by the physics of electricity and the grid's topology. A CAS simulation will test whether any central authority is required, or even desirable, and whether free economic cooperation and competition can, by itself, optimize the efficiency and security of network operation for the benefit of all.

THE BIGGER PICTURE

No one is outside the infrastructure, and there are clearly many opportunities for modeling and simulation, as well as for the use of machine intelligence and human performance engineering. Agent-based modeling and CAS work are only a fraction of what's involved in capturing the level of complexity in infrastructure systems. Modeling complex systems is one of three main areas in CIN/SI's charter. The others are *measurement*—to know what is or will be happening and develop measurement techniques for visualizing and analyzing large-scale emergent behavior—and *management*—to develop distributed management and control systems to keep infrastructures robust and operational. Some specific areas being investigated are

- *Robust control*. Extend the theory of robust control (managing the system to avoid cascading failure in the face of destabilizing influences such as enemy threats or lightning strikes) beyond the relatively narrow problem of feedback control.
- *Disturbance propagation*. Predict and detect the onset of failures at both the local and global levels. This includes establishing thresholds for identifying when instabilities trigger failures.

- *Complex systems*. Develop theoretical underpinnings of complex interactive systems.
- *Dynamic interaction in interdependent layered networks*. Create models that capture network layering at many levels of complexity.
- *Modeling in general*. Develop efficient simulation techniques and ways to create generic models. Develop a modeling framework and analytical tools to study the dynamics and failure modes in the interaction of economic markets with power and transportation systems.
- *Forecasting network behavior and handling uncertainty and risk*. Characterize uncertainty in large distributed networks. Stochastically analyze network performance. Investigate handling rare events through large-deviations theory.

The "Research in the Six CIN/SI Consortia" sidebar lists the consortia, briefly describes their focus, and provides a link to the full research reports.

An October 1997 report from the US President's Commission on Critical Infrastructure Protection cited the growing importance of infrastructure networks in many application areas.[9,10] The PCCIP report and subsequent studies (see "The Challenge of Building Survivable Information-Intensive Systems," pp. 39-43) recognized the damaging and even dangerous ways cascading failures can affect the economy, security, and health of US citizens in unpredictable ways. Indeed, even the weather can create cascading effects. In summer 1998, for example, temperatures were way above normal, the power demand increased, the transmission capacity could not meet it, and prices in the Midwest jumped from $30 to $50 per megawatt-hour to $7,000 per megawatt-hour (http://www.ferc.fed.us/electric/mastback.pdf). Similar price spikes of 100-fold have been experienced during peak demand.

CIN/SI represents a huge undertaking, and long after the initiative is over in 2003, work will continue on the foundation it provides. The EPRI Electricity Technology Roadmap[11] shows approximate milestones for the larger effort to resolve infrastructure vulnerability:

- By 2003, strengthen the power delivery infrastructure. Resolve electric power infrastructure vulnerability threats (CIN/SI).
- By 2005, enable customer-managed service networks. Build an integrated services delivery network as the superhighway system for e-commerce.
- By 2010, boost economic productivity and prosperity. Create the advanced electrotechnology platforms needed to accelerate productivity growth and global competition.
- By 2015, resolve the energy/carbon conflict. Electrify the world to stimulate more efficient patterns of production and consumption.
- By 2025, manage global sustainability.

As these milestones show, CIN/SI's immediate and critical goal is to avoid widespread network failure. Although "resolve vulnerability threats" has many forms—the DoD is more concerned with enemy threats and EPRI with natural disasters and material failures—there is little difference in the effects and recovery task, whether lightning or a terrorist destroys the power pole.

The milestones are ambitious: Achieving and sustaining infrastructure reliability, robustness, and security requires strategic investments in research and development. Given economic, societal, and quality-of-life issues and the ever-increasing interactions and interdependencies among infrastructures, this objective offers exciting scientific and technological challenges. ✷

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