Of Horseshoe Nails and Kingdoms:

Control of Complex Interactive Networks and Systems

Story in Brief

That small events can lead to large effects should be obvious to most of us, given the impact of single oil refinery shutdown on gasoline prices we pay at the pump. Accounting for each small event, however, is hard. For the nation's critical infrastructures, grown large over the years, characterizing small events in terms of their possible impacts has become an important challenge. These infrastructures—energy and others—are so pervasive of modern life that the economic consequences of their failure alone run to many millions of dollars per minute. Yet the very pervasiveness and interdependence of these infrastructures makes them more susceptible than ever to cascading collapses. Tackling this problem for the future, a joint EPRI-government initiative is developing a mathematical basis and practical tools for improving the security, performance, reliability and robustness of interdependent energy, financial, telecommunications, and transportation networks. The first challenges are to develop appropriate models for controlling this degree of complexity and to create intelligent agent tools to enable system components to adaptively reconfigure the network as needed.

By Paul Haase

Introduction: For Want of a Nail

For want of a nail, the shoe was lost
For want of shoe, the horse was lost.
For want of a horse, the rider was lost.
For want of a rider, the battle was lost.
For want of a battle, the war was lost.
For want of a war, the kingdom was lost.
And all for the want of a horseshoe nail.

As suggested by this 16th century adage, the idea of a seemingly trivial happenchance event leading to catastrophe is not new. It was very long ago indeed that thinkers recognized the contingency of events and the possibility of small occurrences producing large effects. But something that is new in recent years is the number and variety of technological catastrophes—blackouts, satellite failures, Internet server crashes, highway gridlock—that can overtake us, their size and completeness, and the possibility that one may precipitate another and another. For the critical infrastructures we rely on continuously to deliver water, power, communications, and all the other necessities and comforts of modern life have become so complex and so interwoven that any small chance event in any single infrastructure presents the possibility (unlikely though it may be) of bringing any or all of the infrastructures down. And as these infrastructures have increased our quality of life so many-fold, so have they become more susceptible to total collapse—and we more helpless without them.

"From a broad historical perspective, reliable networks of energy, transportation, and communication constitute the foundation of all prospering societies," says Massoud Amin, Manager of Mathematics and Information Science at EPRI. "For example, the electric power grid in the United States has evolved over the last one hundred years and it now underlies every aspect of our economy and society; last year it was hailed by the National Academy of Engineering as the 20th century's engineering innovation most beneficial to our civilization. Readers of the Journal who were born before the 1950s or born in developing countries can attest to the critical importance of electricity as a truly enabling force that powers progress and transforms societies."

In Search of a Solution: The Complex Interactive Networks and Systems Initiative

To prevent cascading catastrophes from crippling the critical infrastructures of today and tomorrow—in a sense, to account for each and every horseshoe nail in the kingdom—the United States federal government and private sector in 1998 teamed together in an ambitious endeavor called the Complex Interactive Networks/Systems Initiative (CINSI). The goal is to ensure the robust and efficient operation of complex interconnected infrastructures. As such, CINSI is a 5-year, $30 million Government Industry Collaborative University Research program, jointly funded by EPRI and the U.S. Department of Defense (through the Army Research Office). Six research consortia involving 26 universities were selected for funding from a strong pool of candidate consortia, and work began in 1999. Two electric utilities, Exelon (formerly Commonwealth Edison) and Tennessee Valley Authority, are also participating directly in the program, providing staff expertise, data, test and demonstration sites, and management tools.

An infrastructure collapse scenario, no single part of which is implausible

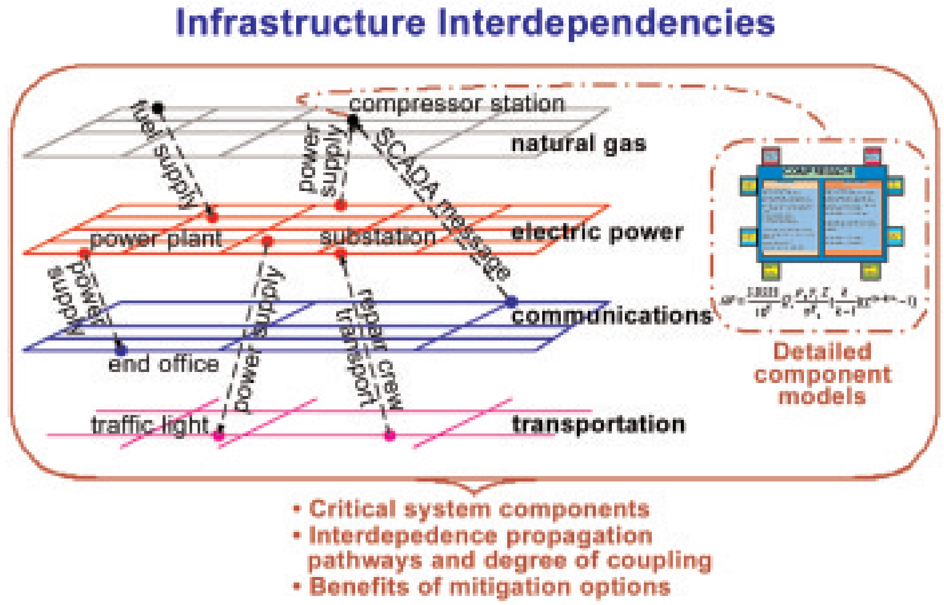
Consider the following scenario. A driver rushing to get home to watch the big ball game races into a busy city intersection too late to beat a red light. He swerves to miss another car and smashes into a light pole. The falling pole takes out the traffic signals for the intersection on its way down, and a large traffic jam develops. Caught some way back in the snarl is a repair crew heading across town to make emergency repairs to a critical compressor on a major natural gas pipeline. The crew tries to phone-in a request for an alternate repair crew, but they can't connect because the local cell is overloaded with calls from all the other people stuck in traffic to check in at work, reschedule meetings, or kill time chatting. So the repair crew sits idling in traffic—which meanwhile is getting worse as cars begin to run out of gas—and repairs don't get made to the compressor. Shortly it fails, and the pipeline loses pressure and shuts down. This cuts off fuel to the local power plants, and they too go out of service. Instantaneously generators across several nearby states work to pick up the unmet electrical load. Power flow on the grid begins to fluctuate, and regional grid operators work to control it. But before the flow of power stabilizes, a large factory in a far-off city happens to switch on a giant reserve printing press to meet additional backorders for the latest "Harry Potter" book, and the immediate electrical demand is too great. Voltage falls, the huge press stalls, and automatic safety devices immediately begin to disconnect generators in several states from the failing grid to prevent damage to equipment and staff. Within a couple of minutes voltage has collapsed everywhere, and the power goes out and stays out. In many states, almost all at once. Regional traffic jams develop because none of the signals function; phone service fades as back-up power for cell towers and repeaters becomes exhausted. Internet servers and routers go down; financial markets close; flights are rerouted and canceled; even the big ball game is called off. Over a multi-state area, modern society comes to complete halt, not because of any natural disaster, war, or weather, but because of the susceptibility of large systems to small events, and the interconnectedness and interdependence of critical infrastructures.

CINSI Consortia

The specified objective of CINSI is to advance the robustness, reliability, and efficiency of the nation's interdependent infrastructures for energy, communications, finance, and transportation. A key concern is the strategic avoidance of widespread network failure due to cascading and interacting effects. The ultimate aim is to develop interconnected networks that automatically optimize and heal themselves after upsets. Even now our critical infrastructures are too becoming complex for continuous and direct human supervision, and the increasing use of automatic microprocessor-based controls to govern these systems adds new complexity in terms of interactions between the devices, cost/benefit analyses, and the potential for unpredicted stability problems.

"The gas supply/pipeline system, the communications networks, and the electric networks are all linked and interdependent," says David Hawkins of the California Independent System Operator. "The value of the Complex Interactive Network projects is to understand the extent of these interdependencies and then how we might apply 'circuit breakers' or safety devices that can minimize the cascading of problems from one system into the others."

Creating robust control for systems no human can fully understand is a difficult challenge. This is what CINSI researchers have set out to do. Though the task may be tough, it is very timely. Large-scale collapse events similar to the "It could happen" scenario are no fantasy; they have already happened. On August 10, 1996, a chance interaction involving trees, transmission lines, and hydroelectric plants running at low power to protect migrating salmon cascaded into a blackout affecting 11 states in the western United States and two provinces in Canada. Power was lost for hours, at a cost of some $1.5 billion. Later analysis revealed that the massive outage would have been avoided if a just tiny fraction of total load (0.4%) on the grid had been shed for just 30 minutes, but there had been no way to realize this fact in the few minutes available to grid operators to take corrective action. Two years later, in May 1998, problems with the Galaxy-IV



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The critical infrastructures that continuously deliver water, power, communications, and all the other necessities and comforts of modern life have become so complex and so interwoven that any small happen-chance event in any single infrastructure presents the remote possibility of bringing any or all of the infrastructures down.

communications satellite disabled nearly every pager in North America—some 40 million of them. Airline flights were delayed, National Public Radio went off the air, and data networks had to be manually switched to older satellites.

"Sometimes disasters are avoided mainly by luck," says Amin, who is leading EPRI's role in CINSI. "In recent years, more than once the hunches and quick actions of power grid operators facing never-before-seen 'close to the edge' situations have saved key parts of the transmission system from imminent collapse during peak demand."

Clearly infrastructure problems are not going away, things are not getting better. The challenge to the security, robustness, reliability, and efficiency of large-scale networks will persist. The U.S. President's Commission on Critical Infrastructure Protection in 1997 highlighted the growing concern. It noted the damaging and dangerous ways that cascading failures can unpredictably affect the economy, security, and health of American citizens. In the area of electricity, the Department of Energy targeted reliability in its 2000 Post Outage Study Team report. This report concluded that the potential for large scale and more frequent power disruptions is higher than at any time since the great Northeast blackout of 1965. Telecommunications are growing increasingly susceptible to satellite failures and other problems, including power outages. Everyone is familiar with the growing problem of traffic congestion on highways and at airports serving large cities. And few beside the U.S. Federal Reserve Chairman Alan Greenspan want to think too hard about the possibility of a major disruption in today's financial markets.

Infrastructures under Threat

Because critical infrastructures touch us all, the growing potential for infrastructure problems stems from multiple sources. These sources include system complexity, economic growth, deregulation, terrorism, even the weather.

The complexity of critical infrastructures is obviously a matter of huge size, pervasiveness, heterogeneity, and nonlinear and uncertain dynamics. Complexity is also a matter of their interdependence The electric power grid relies on the transportation system for deliveries of coal and oil, on the natural gas infrastructure (90% of all new generation planned for construction in the U.S. is natural gas-fired), and on telecommunications networks for data collection and transmission of control signals. Likewise, gas pipelines rely on the power grid

CINSI Consortia

CINSI researchers are focusing on two basic areas of research: 1) fundamental control theory to effectively coordinate the numerous controllers required to reliably operate interconnected networks, and 2) control technology to provide those many controllers. Three of the six CINSI consortia address each area. The objectives and results to date of each of the six research consortia are as follows:

1. Modeling and Diagnosis Methods for Large-Scale Complex Networks. *Consortia members:* Harvard (lead); Boston University; MIT; University of Massachusetts, Amherst; Washington University, St. Louis. *Objective:* The aim is to develop simulation tools based on 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, with focus on power markets. *Results:* Accomplishments to date include development of a detailed model for bidding and analysis of power markets as well as efficient data mining approaches and tools for forecasting and detecting impending failures in complex interactive systems. Already new techniques have been discovered that connect failure characteristics with system topology, and this year they are being put to use to identify "weak-links" in the North American power grid-- there is a recent highlight "Protection Strategies for Cascading Grid Failures-A Shortcut Approach" at: http://www.epri.com/targethigh.asp?program=207896&value=&objid=242218.

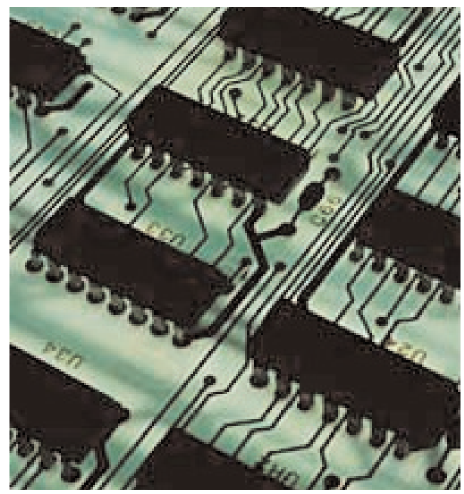
2. Minimizing Failures While Maintaining Efficiency of Complex Interactive Network Systems. *Consortia members:* Cornell (lead); University of Illinois; University of California, Berkeley; George Washington University; Washington State University; University of Wisconsin Madison. *Objective:* The thrust of this effort is to develop computational theories and engineering processes and tools for networked systems and models that maintain efficiency while reducing the likelihood of catastrophic failures. Work involves developing link-based mathematical models for layered networks of infrastructures, characterizing system behavior and failure mechanisms, and quantifying the impact of uncertainty on analysis. *Results:* Development and application of scalable, secure communication protocols optimized for specific application domains such as emerging power system networks; fundamental work on paradigm selection and characterization of failure modes in complex interactive networks; formulation of adaptive power system protection strategy that incorporates link between real-time simulation and control devices. Work continues on characterization of interdependencies, cascading failures (e.g. detailed simulation of NY Power Pool), and other mechanism of network failure; work also continues on disturbance detection and threshold-based security monitoring, and on realistic treatment of variable communication delays in the controlled network environment.

3. From Power Grids to Power Laws: A Mathematics Foundation for Complex Interactive Networks. *Consortia members:* Caltech (lead); Stanford; MIT; University of California, Los Angeles; University of California, Santa Barbara; University of Illinois, Urbana-Champaign. *Objectives:* The focus is on the mathematics fundamental to system optimized to be robust despite uncertain environments. These systems involve power laws due to trade-offs between resource yield and tolerance to cost and risk. These trade-offs lead to highly optimized designs that allow for occasional large events such as major outages. *Results:* Results to date include development of fundamental scaling laws for events such as power outages, forest fires, and Internet congestion, as well as approaches for strengthening the ability of complex networks to resist such events. Further results include: dynamic model reduction for hundreds of generators and large-scale grids, and prediction/prevention of impending disturbances; power system modeling uncertainty and probabilistic modeling-based on small systems, new method for dynamic system reduction.

4. Innovative Techniques for Defense against Catastrophic Failures of Complex, Interactive Power Networks. *Con-*

for electricity to run compressors, traffic systems are dependent on communications to coordinate traffic signals and optimize flow, and so on. At the same time electricity, telecommunications, transportation, and other infrastructures reach deep into our lives, homes, and businesses. Actions in any one infrastructure could contribute to a catastrophe that brings down the entire interlinked complex.

Economic growth in recent years is straining our important infrastructures. A strong economy means more traffic on roads and in the air, more demand for electricity by factories and businesses, more and more phone calls. And new technologies are proliferating that place new demands on old systems, such as the Internet, pagers, and cell phones. Infrastructure construction has not kept pace. During the



1990s, demand for electricity increased some 35 percent while generation and transmission capacity grew by only 18 percent, just half as much. All across North America, the reserve capacity built into infrastructures to relieve bottlenecks and clear disturbances during peak demand is now being used to meet everyday need. In Los Angeles, for example, freeway shoulders and breakdown lanes have been restriped and now carry traffic. Systems as a whole lack slack and are nearer to the edge of total collapse.

Deregulation has compounded problems of capacity by changing the patterns of infrastructure use. For air travel, deregulation has led to the replacement of a robust web of overlapping flight service to a system of hubs-and-spokes that is more eco-

sortia members: University of Washington (lead), Arizona State, Iowa State, Virginia Tech. *Objective:* 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 system-wide considerations. *Results:* To date, a conceptual design has been developed for an adaptive multiagent Strategic Power Infrastructure Defense system applicable to a deregulated marketplace. Established proof of concept and simulation demonstration on WSCC model for an intelligent, adaptive islanding scheme to reduce the probability of cascading failures in power grids and minimize load lost. Preliminary results suggest approaches for identifying (1) where to look for signals that indicate the onset of cascading disturbances and (2) how to control failure propagation and perform adaptive islanding. More detailed modeling of cascading failures is under way, with efforts focused on determining what the signals might be and examining the efficacy of security reinforcement strategies based on the identification and protection of potential vulnerabilities.

5. Intelligent Management of the Electric Power Grid through an Innovative, Anticipatory, Multiagent, High-Performance Computing Approach. *Consortia members:* Purdue (lead), University of Tennessee, Fisk University, Exelon (Commonwealth Edison Co.), Tennessee Valley Authority. *Objective:* This effort is exploring use of agents on local area grids (LAGs), each containing a certain mix of commercial, industrial, and residential loads as well as some standby generating capacity. Within each LAG, adaptive agents dedicated to individual loads and generators predict future local demand and inform the LAG about anticipated conditions in time to do something about them. The main task is to determine internal agent-based operation of the LAGs. *Results:* To date, quantitative criteria have been developed for defining LAGs, and the anticipatory demand-side management and local dispatch strategies the agents would employ have been validated on data from the Exelon and TVA power systems. Other results include: Predictive modeling of loads (neuro-fuzzy approach with wavelet-based signature extraction); automated learning of the consumption patterns and tracking unexpected demand transients; Genetic Algorithm based approach to OPF, generator dispatch and use of energy storage units; development of TELOS (Transmission/distribution entities with on-line self-healing). Simulation testing of an adaptive agent-based system (TELOS) that aims to avert power failures by anticipating the changing demands of electricity consumers and automatically adapting to the daily fluctuations in electricity consumption. TELOS has been demonstrated through simulations, and field deployment of intelligent, adaptive controls in localized areas is being planned for 2003.

6. Context-Dependent Network Agents (CDNA). *Consortia members:* Carnegie Mellon University (lead), RPI, Texas A&M, University of Minnesota, University of Illinois. *Objective:* The objective is to develop appropriate algorithms and computer intelligence for use in designing and deploying on-line context-dependent network agents. Researchers aim to more fully exploit the use of memory, computing, and communication technology in power systems and other complex, dynamic networks. *Results:* Results to date include ground rules governing real-time control of power grids and other complex systems by intelligent agents, specific controls for megawatt-scale voltage and current regulating devices, and an evaluation of the state of reactive power control existing in today's deregulated power markets. Additional results include: On-line context identification techniques for power systems, CDNA strategies for FACTS devices and protective relaying strategies; substation state estimation (using advanced 3-phase state estimation); automated simulation testing of market (auction) preliminary designs for electricity; OPF with incorporation of congestion constraints in the dispatch- sensitivity analysis; coloring electrons: Determination of root causes/entities responsible for losses; power system diagnostics dynamic recording devices (DRD) - Integration of Disturbance Event Analyzer with Fault Diagnostic; adaptive coherency, signal selection for control design, adaptive tuning (applications to FACTS, PSS, etc.).

nomical, and also more subject to delays. In telecommunications, deregulation has promoted all kinds of unforeseen uses for phones and pagers—and new kinds of service problems. For electricity, changes due to deregulation are still unfolding. Already long-distance bulk power transfers have grown more than four-fold since 1995. The power grid, designed for reliability within regional, locally controlled areas, lacks sufficient interties among areas to support heavy-duty long-range transactions. As a result, grid planners and operators are struggling—to date, not entirely successfully—to meet the demands of the new energy business.

In addition to familiar stresses on infrastructure, threats of terrorism and weather cannot be ignored. The present vulnerability of modern infrastructures to cascading problems after chance events leaves these systems open to deliberate interference by terrorists, enemy states, or misguided individuals. The same vulnerability means extreme temperatures and storms disrupt services across the nation. For example the summer of 1998 was much hotter than normal, and the electric power grid was unable to keep up with increased demand. Power prices in the Midwest jumped from around $40 per megawatt-hour to $7000 per megawatt-hour; service to some customers was curtailed. Since then, 100-fold spikes related to weather conditions have been experienced in other parts of the country, and the trend is worsening. More-over, the present high in the 11-year cycle of solar flare activity further threatens the stability of power service as well as telecommunications.

Despite increasing concerns in these areas as well as the continuing erosion of reserve margins, the infrastructures of today do generally function well. The electricity is on, the phones work, traffic flows nearly all of the time. But more and more, the traditional level of performance is no longer good enough. More robust infrastructures are wanted for the "Digital Society" envisioned for tomorrow.

In the electric power area, many call for an increase in reliability from today's average of about 99.9% (approximately 8 hours of outage per year) to 99.9999% (about 32 seconds outage per year) or even 99.9999999% (one outage lasting less than a single ac cycle per year). Such near-perfect power is needed for error-free operation of the microprocessor chips finding their way into just about everything, including billions of embedded applications, these days. Tomorrow's Digital Society will be built on microprocessors—in smart refrigerators that automatically keep themselves stocked with your favorite foods, in smart door locks that know who to let in and when, smart shoes that monitor your daily exercise and physical condition, smart wallets, smart curtains, smart toothbrushes, smart cereal boxes. Adequate microprocessors now cost just a few dollars; before long the price will be a few cents or less. The catch is the quality of electricity service: unprotected microprocessors demand perfect power to function properly. A similar need of perfection exists for other infrastructures, where future advanced systems are predicated on the perfect functioning of today's communications, transportation, and financial services.

"The Complex Interactive Networks Ini-

Actions and Operations Within the Power Grid

Type	Action or operation	Timeframe
Reactive	Wave effects (fast dynamics, such as lighting causing surges or overvoltage	Microseconds to milliseconds
Reactive	Switching overvoltages	Milliseconds
Reactive	Fault protection	100 milliseconds or a few cycles
Reactive	Electromagnetic effects in machine windings	Milliseconds to seconds
Reactive	Stability	60 cycles or 1 second
Reactive	Stability Augmentation	Seconds
Reactive	Electromechanical effects of oscillations in motors & generators	Milliseconds to minutes
React/Coord	Tie line load frequency control	1 to 10 seconds; ongoing
React/Coord	Economic load dispatch	10 seconds to 1 hour; ongoing
React/Coord	Thermodynamic changes from boiler control action (slow dynamics)	Seconds to hours
Coordinate	System structure monitoring (what is energized & what is not)	Steady state; on-going
Coordinate	System state measurement and estimation	Steady state; on-going
Coordinate	System security monitoring	Steady state; on-going
Coord/Strategy	Load Management, load forecasting, generation scheduling	1 hour to 1 day or more, ongoing
Coord/Strategy	Maintenance scheduling	Months to 1 year, ongoing
Strategize	Expansion planning	Years, ongoing
Strategize	Power plant site selection, design, construction, environmental impact, etc.	2-10 years or longer

The electric power grid is a multilayer, multi-scale network. The time scale varies from microseconds to years, which greatly complicates modeling, analysis, simulation, control, and operations tasks.

tiative is important to many industry functions in the United States," says John Haner, Research and Development Manager with Bonneville Power Administration. "It will be extremely important to the U.S. electric power system in identifying safe and reliable operating points based upon statistical means and validated by historical data."

Technology and Theory for Complex Interactive Systems

It's not an easy task for CINSI researchers to tackle modern concerns about the performance and robustness of complex interactive infrastructure systems, because these systems are complicated beyond present computational capabilities and even fundamental mathematical understanding. New control technologies and control theories will be needed before we can view each nail in the context of each kingdom, and the reverse.

Take the North American power grid, which is considered to be the largest machine in the world. The electric power grid has become so complex and interconnected that mathematics barely exist to describe it. That leaves unresolved the matter of control: available computation techniques, data collection technologies, and control theories are inadequate. Events on the grid cannot be simulated in real time as they occur, so operators rely on ready-made analyses and off-the-shelf contingency plans to handle upsets. To develop these plans, grid analysts and planners model possible contingencies: what happens if that line fails when the load here is high and over there is low? What if the load is not so high? What if this other line fails instead, or that generator is out of service, or this particular factory comes on line? What if the weather is especially hot or cold? Each such contingency takes hours to run on the fastest computers available, and it provides only an approximation of the particular situation existing at any time. Planners are running new simulations as fast as they can, but the grid is changing faster.

"It is important to note that the key elements and principles of operation for interconnected power systems were established in the 1960s prior to the emergence of extensive computer and communication networks," says EPRI's Amin. "Computation is now heavily used in all levels of the power network—for planning and optimization, fast local control of equipment, processing of field data. But coordination across the network happens on a slower time-scale. Some coordination occurs under computer control, but much of it is still based on telephone calls between system operators at the utility control centers, even—or especially!—during emergencies."

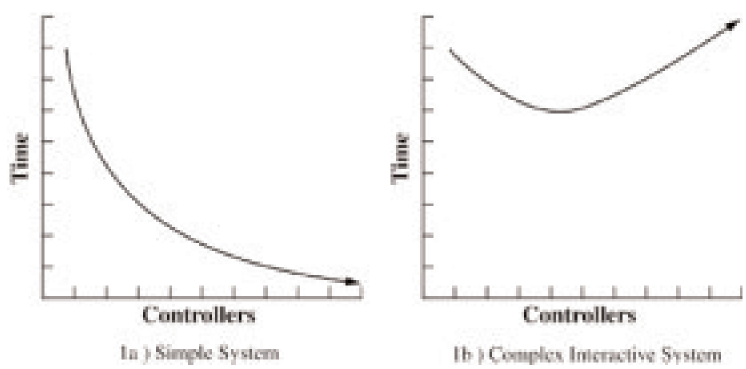
What is true for the electricity infrastructure holds for other critical infrastructures as well. Technologies are insufficient for robust control—each infrastructure has so many "parts" that adequate information cannot be collected quickly enough. Not only are the parts extremely numerous, the time-scale of their actions is extremely varied, from microseconds for lightning strikes and switching operations to years or longer for infrastructure construction. (See table: Actions and Operations within the Electric Power Grid.) There is too much to keep track of—all those nails and horseshoes and riders and battles—any one of which may be the key at any given time.

Inadequate theory is a second problem limiting efforts to govern today's infrastructure systems. Complex interactive systems are not just giant assemblies that can be readily broken down into many small, more-or-less independent parts that can be controlled individually. Instead, components small and large are linked by an intricate internal structure that is difficult to unravel; how one thing leads to another in these systems is not clear. This is the heart of what makes them complex rather than simply gigantic. The problem is not only one of accounting for tremendously large numbers of parts, but also of coordinating and organizing all the parts. And it gets even worse when the interdependencies among different infrastructures—gas, telecommunications, transportation, and so on—are considered.

Complexity manifests itself in controller communications time. For a big but inherently simple system—a 5000-piece jigsaw puzzle, say—communications between the controllers (those assembling the puzzle) is not a significant concern because the parts are more or less independent. One part does not depend strongly on any other part; a group can assemble the puzzle starting from anywhere and no one has to talk much to do it. If there are more parts or you want to faster performance, you can just add more controllers to divide up the work, e.g., for the puzzle, you get some more friends to help. Theory, obvious it may be, is sufficient for large but simple cases.

But control theory is inadequate for complex interactive systems. Here the parts of the system depend strongly on one another. Consequently the controllers for the

Communication time for controls on simple versus complex interactive systems



Complex interactive systems are more than simple systems grown gigantic. A new level of complexity is introduced by the many interactions between the numerous parts of a truly complex system. A simple system can be readily broken into parts that can be controlled independently (i.e., without communications) by individual controllers. If there are more parts, more controllers can be added to control them (Fig. 1a). For a complex system, where all the parts interact strongly, the controllers for each part must coordinate with many other controllers. As a result, the more parts there are in such a system, the longer it takes for the controllers to coordinate amongst themselves, to the point that no controlling gets accomplished (Fig. 1b).

parts have to spend a lot of time passing information back and forth about what is going on with the other parts in order to make a decision about what to do with their part. These decisions in turn impact decisions of other controllers. Things get messy fast. A relationship for such cases was put forth by Frederick Brooks Jr. in The Mythical Man Month: if there are "n" parts in a complex interactive system, the communications required to coordinate the parts will scale as "n2". It is entirely conceivable that all available time could be devoted to communications, with no time spent controlling anything at all.

This result shouldn't be unfamiliar to those in the modern workplace, which represents a kind of complex interactive system in itself. Computers have so greatly changed the capabilities and requirements of individual workers that organizational structures have yet to catch up. Think about all the grousing about endless corporate meetings. What are these but attempts at communication and coordination? These days "Dilbert" creator Scott Adams is enriching himself by playing off the sense of dysfunction in modern organizations.

Decades before "Dilbert," Brooks developed his communications-scaling formula on the basis of his experience managing large, complex programming projects for IBM in the 1950s and 60s: more than once he found that assigning more staff to a project that was behind schedule only made it even more late. Jokes about Army bureaucracy—another approach to control of complex interactive systems—are much older still. Even the very first engineering fiasco—the Tower of Babel—was, according to Biblical legend, due to no problem other than communications. Management Audit of the Babel Project (ca. 3000 BC). Apparently trouble in coordinating complexly interwoven systems goes about as far back as humans do.

Taking Command of Complexity: CINSI Research Activities

New concepts being developed by CINSI researchers promise to overcome the long-standing problem of complexity and control. Work focuses on the two basic areas of development needed to give operators command of complex interactive systems and networks: 1) adequate control theory to effectively coordinate the numerous controllers required and 2) adequate technology to provide those many controllers. Three of the six CINSI consortia address each area.

In the area of new theory, researchers are exploring the measurement and modeling of complex interactive systems. Dynamical systems, statistical physics, information and communication, and computational complexity are being studied in example systems such as power grids and the Internet. Part of the work must determine if there exists a unifying paradigm for simu-

A Management Audit of the Babel Project (ca. 3000 BC)

Now the whole earth used only one language, with few words. On the occasion of a migration from the east, men descended a plain in the land of Shinar, and settled there. Then they said to one another, "Come, let us make bricks, burning them well." So they used bricks for stone, and bitumen for mortar. Then they said, "Come, let us build ourselves a city with a tower whose top shall reach the heavens (thus making a name for ourselves), so that we may not be scattered all over the earth." Then the Lord came down to look at the city and tower which human beings had built. The Lord said, "They are just one people, and they all have the same language. If this is what they can do as a beginning, then nothing that they resolve to do will be impossible for them. Come, let us go down, and there make such a babble of their language that they will not understand one another's speech." Thus the Lord dispersed them from there all over the earth, so that they had to stop building the city. *—Bible, Genesis 11:1-8*

According to the Genesis account, the tower of Babel was man's second major engineering undertaking, after Noah's ark. Babel was the first engineering fiasco.

The story is deep and instructive on several levels. Let us, however, examine it purely as an engineering project, and see what management lessons can be learned. How well was their project equipped with the prerequisites for success? Did they have:

1. A clear mission? Yes, although naively impossible. The project failed long before it ran into this fundamental limitation.
2. Manpower? Plenty of it.
3. Materials? Clay and asphalt are abundant in Mesopotamia.
4. Enough time? Yes, there is no hint of any time constraint.
5. Adequate technology? Yes, the pyramidal or conical structure is inherently stable and spreads compressive load well. Clearly masonry was well understood. The project failed be fore it hit technological limitations.

Well, if they had all of these things, why did the project fail? Where did they lack? In two respects—communication, and its consequent,organization. They were unable to talk with each other, hence they could not coordinate. When coordination failed, work ground to ahalt. Reading between the lines we gather that lack of communication led to disputes, bad feelings, and group jealousies. Shortly theclans began to move apart, preferring isolation to wrangling.

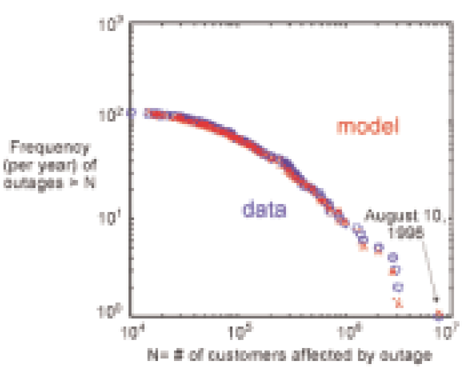
—Frederick Brooks, Jr., The Mythical Man Month (1975).

lating, analyzing, and optimizing complex time-critical operations. A primary objective is to identify any structure internal to complex interactive systems so that they may be most efficiently broken into parts for control purposes.

Already, fundamental research into the structure of complex interactive systems has provided insights into the manner in which small events grow to have large system-wide impacts, and how such events might be contained.

These preliminary findings suggest approaches by which the natural barriers in power grids may be made more robust by simple changes in the system configuration, and eventually how small failures might be contained and stamped-out by intelligent "smokejumper-like" controllers before they grow into large problems. Other CINSI research into fundamental theory of complex interactive systems is exploring means of quickly identifying weak links and failures within a system.

Once the behavior of a complex system can be understood, measured, and modeled, that system still needs to be managed. Thus CINSI research into control of complex interactive systems also addresses techniques for coordinating the many and interacting parts of such systems. Efforts focus on agent technology and distributed tools for measurements, communications, and management.



CINSI research has found that for power outages, the relation between frequency and size appears to be governed by a mathematical formula known as a power law. The same type of relation holds for forest fires and internet traffic, among other things.

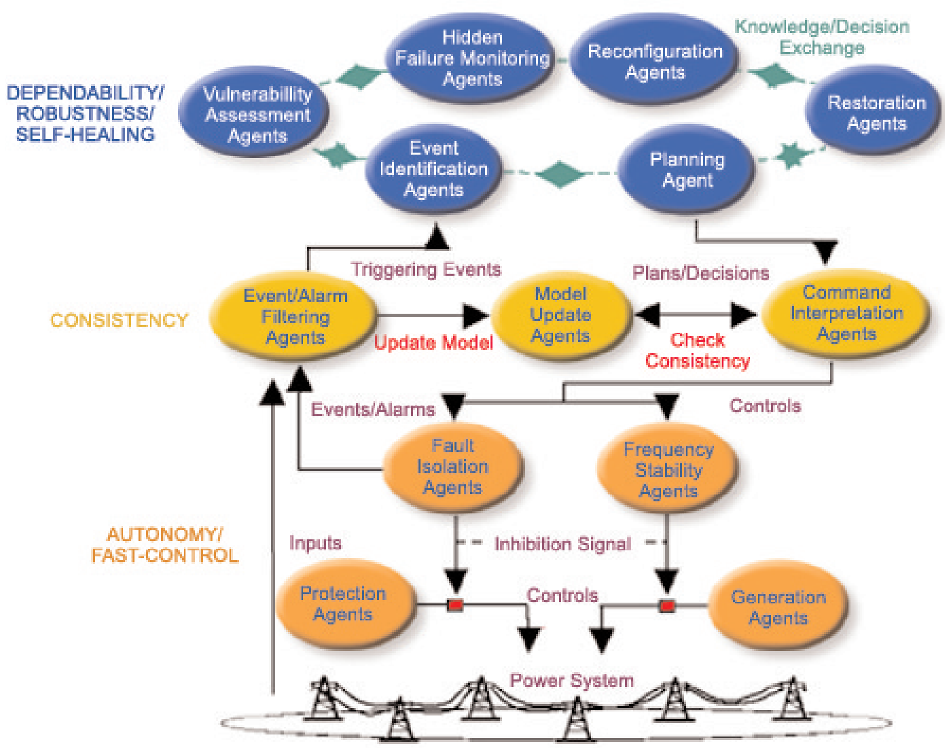
CINSI scientists are exploring agent technology because it provides a near-infinite resource for keeping track of the myriad "nails" in a complex interactive system. An agent itself is any device or system that automatically performs a specific task. The task may be simple (repeatedly turn on for one minute and off for one minute) or complicated (locate the cheapest airfare between two specified cities within a given window of time, avoiding particular airlines and connecting hubs). Simple agents are circuit breakers and automobile warning lights. More complex agents are feedback loop controllers such as traffic lights that automatically adjust their timing depending on traffic flow. The most complex agents exist on the Internet, for searching, filtering, and organizing massive data. This last type of agent represents an active kind of program, a natural outgrowth of object-oriented technology already used by the power grid, financial networks, and other infrastructures. These infrastructures also employ the simplest agents, which may be compared to low forms of animal life that operate instinctively and are unable to learn from their failures.

But ordinary agents such as are used today are insufficient for CINSI purposes, because of the weight of communications necessary for their use in coordinating complex interactive systems and the massive initial programming required to tell each agent what to do in the first place. Rather, researchers are working with a new, intelligent type of agent in the area of complex adaptive systems (CAS). A CAS is an agent or collection of agents that can evolve over time in response to its environment. They do so by combining aspects of neural network, expert system, fuzzy logic, and cellular automata technologies. This provides them with a degree of intelligence as well as automatic evolution and learning abilities.

Automatic learning is a key benefit of CAS agents in a complex system environment. These agents employ a built-in "fitness function" such that those individual agents that most accurately reflect the demands of their environment are copied and those that do not are eliminated. In this way CAS agents can evolve over time to "understand"—in the sense that they correctly characterize the behavior of—the dynamics of a complex interactive system. Through automatic evolution, the agents can learn about their context and environment. If organized in coordination with the internal structure existing in a complex interactive system and with the physics specific to the components they control, these agents promise to provide effective local oversight and control without need of excessive communications, supervision, or initial programming. Indeed, they can be used even if human understanding of the complex system in question is incomplete.

To this end, CINSI consortia are studying control, optimization, problem identification, feedback, and communications for complex adaptive agents, with emphasis on electric power grid applications. One consortium led by the University of Washington has developed a conceptual framework for multilevel adaptive agent control of power grids in a deregulated marketplace. The conceptual system, called "Strategic Power Infrastructure Defense," has three layers. A low-level "reactive' layer handles immediate problems following relatively

Multilevel agent control system for power systems



This framework for multilevel agent control and protection of power grids in a deregulated marketplace has been developed in CINSI work led by researchers at the University of Washington. The conceptual system, called "Strategic Power Infrastructure Defense", has three layers. At bottom is a *reactive* layer of agents. These agents exist in every local subsystem—from "horseshoe nail" up to "kingdom"—and perform preprogrammed self-healing actions that require an immediate response. Such simple agents already are embedded in many systems today, such as circuit breakers and fuses as well as diagnostic routines. At the top is a *deliberative* layer of agents, which develop long-range, large-scale plans such as when to request new infrastructure or how to direct outside assistance. In the middle is a *coordination* layer of agents that constantly communicates with and reviews the actions of bottom- and top-layer agents. This layer is equipped with heuristic knowledge to determine what information needs be communicated for the effective operation of the other levels.

simple rules, a top-level "deliberative" layer develops long-term strategy based on system-wide inputs and analysis, and a mid-level "coordination" layer links the activities of the other two. Hierarchical scaling of information ensures that appropriate amounts and types of data—and none other—are passed to agents at the various levels.

"The Complex Interactive Network and Systems Initiative carried out by EPRI addresses a great number of challenging issue on modeling complex systems," says Dr. Francois-Regis Monclar of Electricite de France, the French national utility. "The many different sub-projects aim to design up-to-date and prospective models and methods taking into account material, environmental, as well as human factors."

Conclusion: The Kingdom

No one is outside the infrastructure, and there are clearly many opportunities for modeling and simulation, as well as the use of machine intelligence and human performance engineering. The CINSI effort represents a first step towards full self-healing control of systems that may be beyond complete human comprehension, such as continental-scale power grids, financial markets, or even whole economies. If successful, there will still remain the difficulty of verifying that such automatic control systems are behaving in an optimal manner, but that may be a problem for another day.

"The CINSI effort, ambitious though it may be, represents just part of a larger, long-term EPRI effort aimed at a sustainable energy future, as described in the Electricity Technology Roadmap," says EPRI's Amin. "Achieving and sustaining infrastructure reliability, robustness, security, and efficiency requires strategic investments in research and development. Given the ever-increasing interaction and interdependencies among infrastructures—not to mention the economic, societal, and quality-of-life issues—this objective offers exciting scientific and technological challenges for the years ahead." ■

Additional Reading

"Complex Interactive Networks/Systems Initiative: First Annual Report: Overview and Progress Report for Joint EPRI and U.S. Department of Defense University Research Initiative." EPRI TP-114660, June 2000.

Massoud Amin, "Towards Self-Healing Infrastructure Systems." IEEE Computer, August 2000, Vol.33, Number 8, pp.44-53.

Massound Amin and Dan Ballard, "Defining New Markets for Intelligent Agents." IT Professional, July/August 2000, pp. 29-35.

Massound Amin, "Modeling and Control of Electric Power Systems and Markets." IEEE Control Systems Magazine, August 2000, pp. 20-24.

Report of the U.S. Department of Energy's Power Outage Study Team, U.S. Department of Energy, 2000.

The Mythical Man Month, Frederick Brooks Jr, Addison-Wesley, 1975.

"Reading the Tea Leaves," Wall Street Journal, 12/31/99, which is available at www.epri.com/targetPressContent.

Selected CINSI Publications to date

To date there have been over 320 publications (published or submitted), and several CD proceedings of the annual reviews and workshops. Seven EPRI reports TP-114660 through TP-114666 were published in May 2000; six EPRI reports are included in kit number E208338 which consists of TR-1006089, TR-1006091 through TR-1006095 published in June 2001. A few of the publications are highlighted below.

"Complex Interactive Networks/Systems Initiative: First Annual Report: Overview and Progress Report for Joint EPRI and U.S. Department of Defense University Research Initiative." EPRI TP-114660, June 2000.

"Development and Analytical and Computational Methods for the Strategic Power Infrastructure Defense (SPID) System—EPRI/DoD CIN/SI Program: Second Annual Report." EPRI 1006089, June 2001.

"Intelligent Management of the Power Grid: An Anticipatory, Multi-Agent, High Performance Computing Approach—EPRI/DoD CIN/SI Program: Second Annual Report." EPRI 1006091, June 2001.

"Modeling and Diagnosis Methods for Large-Scale Complex Networks—EPRI/DoD CINSI Program: Second Annual Report." EPRI 1006092, June 2001.

"Minimizing Failures While Maximizing Efficiency of Complex Interactive Networks and Systems—EPRI/DoD CINSI Program: Second Annual Report." EPRI 1006093, June 2001.

"Context-Dependent Network Agents—EPRI/DoD CINSI Program: Second Annual Report." EPRI 1006094, June 2001.

"From Power Laws to Power Grids: A Mathematical and Computational Framework for Complex Interactive Networks—EPRI/DoD CINSI Program: Second Annual Report." EPRI 1006095, June 2001.

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