Designing Emergent Cyberphysical Control Systems

Proposed Position Paper
NSF Energy CPS Workshop
December, 2013

Arnold B. Urken
Research Professor
Civil Engineering and Engineering Mechanics
Udall Center for Public Policy
University of Arizona
arnieu@email.arizona.edu
520-820-5128

Designing Emergent Cyberphysical Control Systems

Emergent cyberphysical control systems can detect abnormal system patterns as they develop and enable appropriate countervailing action to either restabilize operations or enable "graceful degradation". In restabilization, marginal resources are mobilized to expand system operational capacity to offset internal and external stresses and strains and enable *robust* adaptive delivery of normal system functionality. If robust change is not feasible, *resilient* adaptation is activated to slow down degradation and enable the system to minimize harm to its infrastructure and users. Resilient controls can minimize recovery time and costs (3, 14-16).

The principles of emergent control have been explicated in a study of voltage regulation in electrical infrastructure in which communications infrastructures containing multiple agents was used to monitor, detect and respond to voltage instability (14, 15). The same methodology can be extended to meet control challenges in designing power, transportation, cybersecurity, water, and tsunami systems (4, 12, 13).

Traditionally, the control of electrical systems relied on "overdesigning" systems to enable them to withstand internal and external stresses based on the latest feedback. Conventional adaptive management focuses on periodically updating intelligence about system operations to adjust reserve power margins and plan for the future. This focus results in a reactive mentality instead of a proactive strategic framework. Serious and potentially catastrophic power grid failures could still undermine reserve calibrations today in sizable grids even if updating time were cut in half. And power infrastructure capital project planning is still hampered by an uncertain time horizon in which the occurrence of low-probability, forseeable events makes it necessary to assess and respond to unpredicted challenges that are ambiguous or ambivalent (1, 14, 15, 17).

Multiple agents can control the emergence of voltage variability by sampling voltage patterns at the millisecond level and reaching reliable collective inferences about changes in voltage direction and magnitude. Operating in centralized and/or peer-to-peer networks, agents communicate rating information about voltage changes across a network to produce collective inferences about the state of the voltage system. Network communications based error-resilient data fusion (ERDF) techniques makes it possible to produce collective intelligence that will be reliable despite transmission breakdowns or delays and in spite of imperfections in individual agent reliability. ERDF systems make use of a voting framework in which agents allocate votes to express complex rating information about a well-defined set of options and transmit voting data across a network to form an error-resilient collective outcome (ERCO). An ERCO is a collective outcome that contains aninference that 1) occurs at any point during data collection before all votes have been received or processed, and 2) will not be changed if and when all the data arrive. Time constraints can lead human or machine agents to make choices that seem reasonable—but are not—or not select options that seem too risky—but are not. ERDF controls make it possible to avoid the limbo and fog of uncertainty without making practically irreversible choices that may exacerbate instability (9-14).

In ERDF systems, ERCOs can occur even when agents express uncertainty in different ways including acknowledgement of insufficient information, expression of fuzzy patterns, and/or multidimensional representations. Moreover, since false positives and false negatives can be modeled *as if* they were attributes of individual agent/voter decision making, network communications based on ERDF principles can be designed to minimize or dampen failures.

Human-centric interfaces for robust system management have been eclipsed by the growth of complex dynamic systems that operate at multiple physical and time scales that go beyond human cognitive and operational capacities

(16, 17). But networks of computer devices could produce collective inferences to augment the scope and domains of human control. For example, ERDF inferences provide a window of opportunity for verifying intelligence, taking precautionary action, or recommending/implementing sequences of appropriate countervailing action. Instead of being overwhelmed by "big data," humans could be supported by targeted timely, accurate collective intelligence that enhances human capabilities.

Voting systems provide a communications structure that includes semantics and syntax for relating low-level data to high-level inferences about network situations. Reportedly, animals gain evolvability from using the time and resource benefits of vote-based communications to make critical decisions that affect their survivability (6, 12). However, more work needs to be done to clarify current experimental and theoretical results. Current research suggests that human or machine agent collective action can be used to manage tradeoffs between speed and accuracy in regulating internal and external system disturbances. Still, the challenges of detecting and controlling the destructive force of interdependent failures across many types of control systems can undermine the sustainability of social structures at many levels and in multiple dimensions.

Imagine the following types of emergent cyberphysical controls based on ERDF communication:

- Cybersecurity:
  - Agent scout patrols that collectively detect and manage abnormalities in network traffic
  - Collective agent authentication of users for network access
  - Autonomous, coordinated offensive ad hoc action inside hostile network environments
  - Collective intelligence that distinguishes in-cast problems from DOS attacks and manages pro-active responses
- Transportation:
  - Collective detection of and response to unexpected obstacles on high-speed train tracks or "superbus" pathways to avert or minimize collisions
  - Averting/minimizing double man-machine systems failures such as the 2008 DC Metro crash
- Tsunamis
  - Flexible centralized/peer-to-peer monitoring of disturbances to enable local and global coordinated actions
  - Control mechanisms that regulate false positives <u>and</u> false negatives
- Water
  - Real-time detection of water contaminants and coordinated network response
  - More efficient and reliable real-time control of electricity in semiconductor FABs to control maximum and minimum voltage

Einstein suggested that imagination may be more important than knowledge because it leads to new ways of thinking that enable our knowledge to grow. Emergent control systems based on ERDF methodology provide a new way of imagining the design of adaptive control mechanisms that can tell us how much data agents must collect, how long they must wait, and how information can be represented and fused to produce reliable, time-engineered collective inferences about control.

References

1. Cano-Andrade, S., von Spakovsky, M.R., Fuentes, A., Lo Prete, C., Hobbs, B., and L. Mili, (2012) "Multi-Objective Optimization for the Sustainable-Resilient Synthesis/Design/Operation of a Power Network Coupled to Distributed Power Producers Via Microgrids," Proceedings of IMECE2012, 2012 ASME International Mechanical Engineering Congress and Exposition, November 9-15, 2012, Houston, Texas.

2. Gheorge, A. V. (1985) "Paradigms in Energy/Time Relationship," in Energy and Time in the Economic and Physical Sciences, van Gool, W. and Bruggink, J.J.C. (eds.), Amsterdam: North-Holland.

3. Mili, L. (2011) "Taxonomy of the Characteristics of Power System Operating States," NSF-VT Resilient and Sustainable Critical Infrastructures (RESIN) Workshop, Tucson, Arizona.

4. National Research Council, (2006) "Drinking Water Distribution Systems Assessing and Reducing Risks," National Academy Press.

5. Savulescu, C.S. (2005) Real-Time Stability in Power Systems, Springer.

6. Seeley, T. D., and P. K. Visscher. 2004. "Quorum sensing during nest-site selection by honey bee swarms," Behav. Ecol. and Sociobio., Vol. 56, pp. 594-560.

7. Urken, A.B. (1988) "Social Choice Theory and Distributed Decision Making", in R. Allen, ed., Proced. IEEE/ACM Intl. Conf. on Off. Info. Systs.

8. Urken, A.B. (1990) "Coordinating Distributed Actions via Agent Voting", Proced. IEEE/ACM Intl. Conf. on Off. Info. Systs.

9. Urken, A.B. (2003) "Time, Error, and Collective Decision System Support", Intl. Conf. on Telcom. Systs.

10. Urken, A.B. (2005) "Using Collective Decision System Support to Manage Error in Wireless Sensor Fusion**",** Intl. Conf. on Infor. Fus., Philadelphia.

11. Urken, A.B. (2011a) "Time in Voting Theory", Gide Intl. Conf. on Ec. Analys, Toulouse, France.

12. Urken, A.B. (2011b) "Voting Theory, Data Fusion, and Explanations of Social Behavior", Symp. on Modeling. Voting Systems as if they were Complex Dynamic Systems, Am. Assoc. for Artif. Intel., Stanford.

13. Urken, A.B. (2012a) "Real-Time Control of Water Quality" WateReuse 11-01 Workshop, University of Arizona.

14. Urken, A.B., A. Nimz and T. Schuck (2012b) "Designing evolvable systems in a framework of robust, resilient and sustainable engineering analysis," J. of Advaced Eng. Informatics 26 (2012) 553–562.

15. Urken, A.B. (2013a) "Social systems and Smart Grid optimization: Future electrical grid adaptive control mechanisms" Springer Handbook on Smart Grid Optimization."

16. Urken, A. B. (2013b) "Fusing Data in Adaptive Agent Control Systems for Electrical Grids", Special Issue of the International Journal on Critical Infrastructures, accepted for publication.

17. Weick, K.E. and Sutcliffe, K.M. (2007) Managing the Unexpected: Resilient Performance in an Age of Uncertainty, Jossey-Bass; 2 edition.