Special Issue on Digital Ecologies

THERE IS no doubt that our world has evolved to be complex, with life having emerged as the ultimate manifest of self-organized superior structure. While biologists wonder at the miracles that evolution has created trying to decipher its mysteries, we electrical and electronics engineers have found high delight in competing with the natural complexity to create more and more sophisticated technological artifacts that are enriching our lives, yet seamlessly increasing its complexity. With information communication technologies (ICTs) pervading everyday objects and infrastructures, the "Future Internet" is envisioned to leap toward a radical transformation from how we know it today (a mere communication highway) into a vast digital ecology acting as a vital ganglion of the current globalized society and economy and controlling critical infrastructures on a global scale. Intertwining a complex ICT system (as the Internet can well be considered) and a physical complex system (as, for example, the electrical power grid) is leading to what are usually referred to as *cyber–physical systems*. As a cyber–physical system, a digital ecology is an open ICT control infrastructure in which interconnected interdependent systems of systems weaved by the Internet together with social networks of prosumers (producers and consumers) of applications and services coexist and coevolve, in much the same way as different species share the resources of a common habitat and provide mutual benefits in an ecosystemlike manner. By including the users themselves as key players in the global collaborative ecosystem, its complexity is approaching (if not already reached) the complexity of naturally evolved systems.

The authors featured in this Special Issue push the frontier of interdisciplinary knowledge to be able to engineer and architect large-scale networks of smart cooperative systems by addressing fundamental challenges in the design and operation of new massive-scale complex computing and communications technologies and apply them to enable the seamless and ubiquitous interconnection of diverse environments and smart infrastructures. Present academic knowledge of systems and current practice in the public and private sectors must be radically reconsidered in the light of global interrelated challenges like climate change, sustainability and security or the current financial crisis that need system-wide global coordinated action, grounded in a new type of science that links data, models, and social decision processes.

Systems thinking is the foundational study that needs to be undertaken in global systems science. A better understanding of the boundaries between models is urgently needed to find the answers to difficult questions such as: What are the implications of linking existing models of systems into a coordinated whole? How far do we need to move beyond integration of current models toward conceptualization of truly holistic models that not only combine but also actually fuse knowledge from different domains, points of view, and disciplines? What are the dangers of such fusions? In "Systomics: Toward a Biology of System of Systems," Sauser *et al.* address these difficult points through a novel approach to thinking about the world, which they coined "systomics." Rooted in the observation that biological systems show remarkable properties in terms of robustness and resilience in adapting to new unforeseen conditions and of evolving new features and capabilities, while being able to successfully deal with scale issues, they identify the major characteristics that make the DNA of a system of systems. Narrative, analogy, and interactive communicative technologies are identified as important factors in increasing the applied potential of systems modeling.

Systems modeling require the development of infrastructures for big models to answer questions of relevance to the challenges faced and the decisions to be made, which rely on large-scale data structures to test and correct the models. In "Self-Organized Data Ecologies for Pervasive Situation-Aware Services: The Knowledge Networks Approach," Bicocchi *et al.* propose novel forms of data gathering involving individual agents moving across system domains. They are looking at calibration of data as a significant issue tackling the problem of gathering data on the right level and of the right type while acknowledging the challenge in dealing with the mismatch between scale and type. Sensor-based gathering of temperature and noise-level information, for example, allows collection of data on totally new scales. The use of mobile phones for this seems a particularly powerful way of getting ordinary people involved, as it could integrate subjective data (moods and opinions) and scientific readings. The main conceptual limitations of the current "smart cooperative systems" approach that attempts to divide the global task into small independent segments taken care of by independent agents are identified while addressing the challenge of designing the right interaction protocols and feedback mechanisms that will ensure self-organization. Data gathered in this way could, if socially accepted, induce widespread opinion dynamics, leading to changes in behavior. Investigating eHealth ecosystems, Hadzic and Chang in "Application of Digital Ecosystem Design Methodology Within the Health Domain" tackle the way both top–down and bottom–up constraints produce marked and often unpredictable alterations of behavior in different parts of a system. They are innovatively using the electronic health record as the DNA laying the foundation for a new way of modeling that brings about the synergies from all the data necessary for addressing the particular health problem.

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Journeying from systems biology to molecular communication, Carreras *et al.* in "Bottom–Up Design Patterns and the Energy Web" investigate biologically inspired techniques for designing the building blocks of an *autonomic digital ecosystem* as a framework for steering large-scale technosocial systems by catalyzing and reinforcing beneficial collective user behavior. They consider "*evolve-ability*" as a fundamental and constituent property of digital ecologies in which entities are expected to spontaneously cooperate in order to accomplish the desired tasks. With an example of digital ecosystem that promotes energy efficiency, they illustrate how the digital ecology works as a *socially smart* cybercontroller acting like a "social-network operating system" that leverages on the community via an incentive-driven mechanism. The digital ecology mirrors the "invisible hand" of the market fostering self-organization of groups around a particular tradeoff of the incentive mix to achieve a particular goal (e.g., "greening" the economy).

The dynamics of such large-scale energy webs integrating the communication network as cybercontroller is often underestimated at both modeling- and policy-level efforts. In "Modeling of Future Cyber–Physical Energy Systems for Distributed Sensing and Control," Ilic *et al.* undertake this challenge by making the point that, depending on the speed or throughput of information, dynamic systems can behave predictably and smoothly. They introduce a novel model that can be used to ensure full observability through a cooperative information exchange among its components and illustrate how unpredictable shocks arise when the control mechanism of dynamic systems cannot cope with the flow of new information, by placing a clear emphasis on the global system dynamics and policies. This is achieved without requiring local observability of the system components. The paper also shows how this cyber–physical model is used to develop interactive protocols between the controllers embedded within the system layers and the network operations seamlessly incorporating nonconventional energy-converting components such as fuel cell and photovoltaic devices.

The inherent risk of cascading failures in cyber–physical systems makes it impossible to identify all potential vulnerabilities of such systems, and finding solutions to reduce the failure probability becomes a very difficult and ambitious task. Conceptually, both "sustainable development" and "dynamic systems thinking" touch on resilience, an idea which is increasingly defining human subjectivity in the wake of the security, environmental, and financial shocks of the past decade. Addressing these challenges, Ten *et al.* in "Cybersecurity for Critical Infrastructures: Attack and Defense Modeling" propose an approach to "design for resilience" of eNetworked critical infrastructures, with emphasis on future electric power networks. They make sense of the interdependences between the communication and electricity networks (on which all other infrastructures critically depend) to craft the resilience of the overall system.

Deepening further into these explorations, Alderson and Doyle in "Contrasting Views of Complexity and Their Implications for Network-Centric Infrastructures" propose a breakthrough approach to the design for resilience of networked systems of systems. They postulate that engineering theories of control (cybernetics) communications and computing can be explicitly rephrased mathematically in terms of the construction and verification of the barriers that separate acceptable from unacceptable behaviors—where the latest typically involves a cascading failure event. Based on the observation that *technological evolution* reveals new aspects of complexity contrasting the physicists' and biologists' view of "self-organized criticality," they adopt the concept of highly optimized tolerances, which claims that highly evolved systems, be they biological or technological, display clear architectural features strengthened by protocols that ensure robustness in the complex interplay of the smart cooperative systems linked. The essence of this robustness is the elaboration of highly structured communication, computing, and control networks that also create barriers to cascading failures. This paradigm shift has the potential to transform the entire field of networked infrastructures by infusing robustness in the architectural outfit through reconfiguration strategies to maintain system integrity and functionality by engineering resilience in a more "organic" manner.

This is our quest. In our race for technological growth, we have approached and are competing with nature! Thus, the loop is beautifully closing as we finally reached the point in our evolution from where we can help decipher the mysteries of evolution itself by observing the way we actually create it supported by our technologies. Where are the limits of the impossible? And are we ready to touch them with the same daring attitude which fuels our drive to push continuously the technological frontiers?

If you will find some of the answers journeying throughout our Special Issue, we have reached our purpose. Enjoy!

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Mihaela Ulieru (S'93–M'95–SM'02) received the Ph.D. degree in diagnostics and controls of dynamical systems from the Darmstadt University of Technology, Darmstadt, Germany, in 1995.

She was a Postdoctoral Fellow in the Intelligent Robotics and Manufacturing Group led by Prof. William Gruver at Simon Fraser University, Burnaby, BC, Canada, from 1996 to 1998. She was a Member of the faculty with Brunel University, Uxbridge, U.K., and with the University of Calgary, Calgary, AB, Canada, where she held the Junior Nortel Chair in Intelligent Manufacturing and founded the Emergent Information Systems Laboratory. She has been holding the Canada Research Chair in Adaptive Information Infrastructures for the e-Society since 2005 when she also established (with the Canada Foundation for Innovation funding) and leads the Adaptive Risk Management Laboratory (ARM Lab), researching complex networks as control paradigm for complex systems to develop evolvable architectures for resilient e-networked applications and holistic security ecosystems. In 2007, she was appointed to the Science, Technology and Innovation Council of Canada by the Minister of Industry to advise the government and provide foresight on innovation issues related to the information communication technology (ICT) impact on Canada's economic development and social well-being against international standards of excellence. She has held and holds appointments on several international science and technology advisory boards and review panels, among which are the Science and Engineering Research Council of Singapore, the Scientific Council of the EU Proactive Initiative on Pervasive Adaptation (PERADA), the EU Network of Excellence in Intelligent Manufacturing (IPROMS), and the Natural Science and Engineering Research Council of Canada's Advisory Panel on International Strategy, and as an expert on its ICT and security review panels, as well as the U.S. National Science Foundation Cyber-Systems and several EU FP7 expert panels. To capitalize on her achievements and expertise in distributed intelligent systems by making ICTs an integrated component of policy making targeting a safe, sustainable, and innovation-driven world, she recently founded the Innovation Management and Policy Accelerated by Communication Technologies (IMPACT) Institute for the Digital Economy, for which she currently acts as President.

Dr. Ulieru, as a member of the Administrative Committee of the IEEE Industrial Electronics Society (IES), founded the international industrial informatics research community and its two major forums: the IEEE Industrial Informatics Conferences and the IEEE-IES Industrial Agents Technical Committee. She also founded the IT Revolutions Forum and was the General Chair of its first conference held in Venice, Italy, in December 2008.