## Multi-Disciplinary Challenges and Directions in Networked Cyber-Physical Systems<sup>\*</sup>

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**Introduction.** Cyber-physical research is an inherently multi-disciplinary endeavor and should involve all relevant research communities—and their varied concerns. In this position paper, we sketch a path toward multi-disciplinary research by discussing technical challenges, abstractions, metrics, tools, research directions, and their educational implications.

A New Calculus. We need a mathematics that merges the cyber and physical worlds at a fundamental level. While the nascent field of hybrid systems deals with systems that have both discrete and continuous components, its *limitations* are that the constituent continuous models are still based on a notion of globally shared time. However, in highly interconnected cyber-physical systems, components interact asynchronously at event times. The *challenge* is to formulate a new calculus that merges time-based to event-based systems. We need it to be applicable to hierarchies that involve dynamics at drastically different time scales (from months to microseconds) and geographic scope (from on chip to off world). Furthermore, signal processing and computer control today is based on the bedrock notion that sample times are equidistant, deterministic, constant, and synchronized. However, when systems are interconnected via the Internet, transmission delays, jitter, and packet drops lead to an immediate breakdown of these assumptions. A promising direction is provided by research in the area of "Networked Control Systems."<sup>1</sup> However, we need a completely new systems theory that can deal with time scales that are not equal, where the next update time is only bounded or given by a probability distribution. A milestone would be a theory that enables mainline scientists and engineers to deal with problems that will be commonplace in tomorrow's cyber-physical world, including data aggregation from sensor networks and the remote operation and control physical plants (e.g., robots, infrastructure).

**New Metrics.** Cyber-physical research should be evaluated along metrics that are relevant for all involved communities and that represent a variety of concerns. Real-time distributed systems have been analyzed assuming (1) purely network-related metrics, such as delays or jitter, or with (2) control-theoretical objectives, such as stability, but under fixed network characteristics. These evaluation approaches promote the isolation of different areas of expertise. The compartmentalization of research makes intricate problems more tractable, but at the same its *limitation* is that it can decrease the potential effectiveness of a networked

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<sup>&</sup>lt;sup>1</sup>Zhang et al. Stability of networked control systems. *IEEE Cont. Systems Mag.*, 21(1):84-99, Feb. 2001.

cyber-physical system, and reduces the opportunities for multi-disciplinary research. The challenge is to formulate a methodology that maps networked-oriented metrics into systems performance. An analogous process is done in VoIP, where ITU standards provide formulas to associate delays, jitter, loss rates, and bandwidth with MOS (Mean-Opinion Score) ratings that denote the user's satisfaction with a certain level of voice quality. A milestone for the next 5–10 years is to direct research in disparate communities toward a shared set of metrics and goals. A *promising direction* is the set of benchmarks and metrics for distributed haptics.<sup>2</sup> The objective is to create an evaluation method that is analogous to an ITU standard for VoIP and that translates network-related metrics into user-perceived performance. The haptics evaluation framework aims at the semi-automatic evaluation of distributed haptics over various network configurations. The framework would include a benchmark suite of representative tasks and the infrastructure for network emulations. The benchmark tasks should be (1) simple enough that they can be programmed with control techniques of general knowledge; and (2) representative of simple operations of a human user. One benchmark can be the standard Fitts' task using Fitts' index as a metric. Alternative benchmarks might include tasks requiring trajectory tracking. Another promising direction is the emphasis on disturbance rejection to evaluate play-back buffer effectiveness.<sup>3</sup> Additional issues include metrics for scalability, security, interoperability, and metrics' impact on requirements-services interfaces.

New Software Toolsets for Co-Simulation and Co-Design. A *challenge* is the creation of powerful new simulation and design tools that can handle the distributed and diverse nature of both the cyber and physical worlds. Modeling and simulation is crucial to the understanding and control of physical systems (a common tool for formulating, simulating, composing, and maintaining such models being Matlab/Simulink). The way these systems interact is no longer by sending continuous signals over dedicated wires, but by sending packets over a global network consisting of network interface cards, antennas, routers, switches, and other network components. Such systems can be simulated accurately using powerful event-based tools, such as ns-2. The mixture of the cyber and physical worlds means that we need powerful new software for co-simulation and co-design. These toolsets will be crucial for formulating, simulating, composing, maintaining, and sharing mixed cyber-physical models. A *milestone* would be a complete toolset for predicting, building, verifying, validating, and understanding cyber-physical systems. *Promising directions* are the TrueTime (www.control.lth.se/truetime) extensions to Matlab/Simulink and the Agent/Plant interface between ns-2 and physical modelig.<sup>4</sup>

**New Network Control and Middleware.** Networked sensors and actuators can monitor a physical environment to enable fast response to environmental conditions (e.g., power plants, where substantial savings and operational efficiencies will follow from more accurate and responsive management of power generation). A major *challenge* is that these messages

<sup>&</sup>lt;sup>2</sup>Liberatore et al. Evaluation methods of a middleware for networked surgical simulations, MMVR 2006. <sup>3</sup>Liberatore, A play-back algorithm for networked control, INFOCOM 2006.

<sup>&</sup>lt;sup>4</sup>Branicky, Liberatore, Phillips. Co-simulation for co-design of networked control systems, ACC 2003.

are time- and (often) life-critical, and cannot be subject to the same vagaries of "best effort" delivery if safety and performance are to be maintained. *Promising directions* are the investigation of bandwidth allocation protocols, new queuing strategies, and new routing schemes (including network partitioning) that enable distributed real-time software to be developed despite delays, delay jitter, and packet dropouts. We also need network middleware that provides for real-time resource allocation, distribution of an accurate time base (going beyond NTP toward IEEE 1588 at a global scale), and the ability to monitor, observe, and request ("certificates" guaranteeing) QoS. A *milestone* would be a software distribution that provides support for all of the above and that is freely available, yet practical for industrial use (much like TAO/CORBA in the area of real-time distributed systems).

New Foundations for Science and Engineering Education. To deal with a ubiquitous cyber-physical world, we need scientists and engineers that are heavily trained in the fundamentals of computation, networking, and software engineering. Indeed, these skills are so basic—and the need for interdisciplinary work so crucial—that they must to be added to the lingua franca of all technical graduates. We currently expect all scientists and engineers to have a mastery of mathematics and physics. They are heavily trained in these areas, often taking four semesters of math and three or more of physics at the undergraduate level. The *milestone* of competitive problem solving in the cyber-physical realm requires new competencies. It is time for computer science (and mathematics other than calculus and differential equations) to form new foundation stones for all undergraduate scientists and engineers. A *promising direction* is Lee & Varaiya's Structure and Interpretation of Signals and Systems.

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