

Network Control for Cyber Physical Systems : Position Paper

Information and control: a bridge between the physical and decision layers

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Cyber-Physical Systems (CPS) require the integration of a heterogeneous physical layer and a virtual global decision and control network, mediated by decentralized and distributed local sensing/actuation structures. Applications and instances of CPS are present in many diverse technological areas, including among others energy, transportation, telecommunications, environmental monitoring, biomedical and biological systems. Current CPS design suffers from many issues such as *scalability*, *robustness*, and *performance satisfaction*.

In such systems, direct information about the physical world is usually acquired through a number of local entities, which can be geographically extended (e.g., nervous system, sensor networks), and are often of a heterogeneous nature (e.g., temperature, audio, chemical). The operation and performance requirements are global in nature, and are often represented and expressed in terms of aggregate properties of the overall system (e.g., degree of maneuverability of an airplane, survival, prediction of power outage). The management of such systems entails the integration between a physical layer, which includes the underlying physical system as well as the fixed architectural constraints, and a virtual layer which addresses the design of the information layer and the supporting decision protocols which is designed to achieve a global set of objectives. The information layer is designed to be *flexible*, *reconfigurable*, and *modular* in order to deal with dynamic uncertainty, complexity, and resource limitations in communication and computation, and as a result, its design is intertwined with the decision systems. In order to insure tractability, this interconnected system is designed to be scale-dependent, encoding different levels of abstractions mirrored by different (possibly hierarchical) layers of decision systems. For example, an application involving a networked fleet of mobile sensors and actuators (agents) has various layers of decisions: decisions on connectivity of agents, local decisions by each agent (local utility), and a global strategy communicated to all agents (global utility). In such an example, the interacting layers are indexed by time (indicating the relative speed of variation) and space (indicating the local vs. global nature of decisions).

The operation and control of a cyber-physical system is therefore a complicated task, involving the direct interaction of the physical substrate with the virtual abstractions used in its design, analysis, and verification. The profound incompatibility between these frameworks (layers) has stimulated the use of ad-hoc and informal techniques for CPS

design. Given these difficulties, the current design of cyber-physical systems often relies on a combination of traditional and rule-of-thumb engineering techniques, such as an unwarranted reliance on scale separation (either in time or space), that often fails to provide adequate performance guarantees (e.g., network security or power network failure issues).

Due to this inherent complexity and lack of mathematical and technological tools, in our view the three fundamental components in the design and analysis of present and future cyber-physical systems should be:

- Development of systematic mathematical and computational frameworks on which to model, design, and reason about cyber-physical systems. Very detailed models are inappropriate (for conceptual and computational reasons), while the simplest models can be too conservative.
- Design of information architectures that are flexible, reconfigurable, and modular that can enable a rich class of decision systems. This will capture questions that deal with sensor/actuator placement, the specifications of communication networks, middleware, modes for sharing information, multiplexing and sharing computational components, autonomy, reusability of multi-purpose units, and synchronization of embedded software.
- Design of decision and information management systems. This entails the design of distributed protocols that intend to fuse various data sets from multiple sources, in order to provide real-time decisions that can deliver the intended global performance objective. This will address questions related to hierarchy in decision making, information exchange between various levels in the hierarchy, scheduling, software verification, resource allocation, and ultimately, reconfiguration of architecture to meet the intended performance objectives.

There are several theoretical and practical difficulties in the systematic design of decision and control schemes for cyber-physical systems. Among the most important missing pieces in our current knowledge is a satisfactory understanding of basic architectural issues, both at the modeling, interface, and information levels. The practical difficulties in centralized approaches (e.g., bandwidth, latency, scheduling, fragility, etc.) can in principle be overcome by decentralization, although this brings many additional complications. The components of a systematic study of CPS described earlier immediately motivate and justify the following research challenges:

- Development of flexible modeling techniques that take into account the many possible uses of a given model (such as design, analysis, simulation, verification, etc) and are tuned to the performance objective. In particular, there is a strong need for explicit mechanisms for model management, reduction, and abstraction, as exemplified for instance, in multiscale or multiresolution-like approaches.

- Techniques to manage uncertainty, robustness, and complexity. While much progress has been made in specific model classes (e.g., linear systems, timed automata, etc.), there is little connection yet between the continuous and discrete realms, particularly with an eye towards effective computational methods. The explicit real-time physical requirements impose additional difficulties.
- Design of parametric information architectures that enable local autonomy. The interaction of multiple local entities under incomplete information takes us to the realm of multi-person decision-making. Game theory and the related area of designing game forms (mechanism design) provides a natural framework to design architectures that can enable local autonomy, which can be reconfigured in response to environmental and priority changes. In game theoretic approaches, each player (agent, entity) is endowed with a (potentially parametric) utility function and information set, and is assumed to take actions to maximize its utility according to the available information. Game forms determine how different players interact, as well as the exact information available to different players at the time of their actions.
- Computationally tractable methods for the design of distributed decision protocols are also lacking. A primary reason is the lack of pragmatic modeling of the underlying system constraints. Such models and methods may be derived from the game theoretic/mechanism design framework.
- Large-scale systems and statistical mechanics. A particular interest is in developing methodologies to study the approximate system behavior under scaling of system in terms of space, time etc. Such approximations can lead to simple characterizations of system invariance and fundamental limitations.
- Deeper understanding of the process of integration and fusion of local information into a global state of the system. Ideas of geometry and topology seem natural in this context, although many technical difficulties need to be resolved.

Addressing the above challenges will require a combination of significant theoretical advances and new perspectives.

Our team consists of researchers who have worked extensively in control theory, information theory, optimization, networks, and game theory, and thus brings together the essential ingredients necessary to lay out the foundations of a systematic study of CPS. The approaches we are currently developing include system interconnections, reduction, and model approximation through scaling laws. They also include problems of control with fixed information structures in order to understand the fundamental limitations and capabilities of such distributed control design. The research addresses consensus algorithms that can be viewed as methods for computing global quantities by distributed computation utilizing local information. Finally, our research also addresses aspects of network economics and mechanism design issues, such as how rewards to local decision makers should be designed so that their actions are aligned with a global

objective. **All members of this team are internationally known for their contributions in these areas, and are associated with the Laboratory for Information and Decision Systems, MIT.**