Position Paper:
Human-Cyber-Physical Systems for Emergency Response

A. Ames[1], M. Branlat[2], R. Murphy[3], D. Song[3], D. Woods[2], J. Valasek[4], T. Zourntos[5]
[1]Mechanical Engineering, Texas A&M, [2] Cognitive Engineering Lab, Ohio State
[3] Computer Science, Texas A&M, [4]Aerospace Engineering, Texas A&M,
[5] Electrical and Computer Engineering, Texas A&M

corresponding author: Robin Murphy, murphy@cs.tamu.edu

Prior successes in CPS, especially addressing hybrid discrete and continuous control, has led to advances in unmanned systems, embedded sensors, and network technologies. One area of application of these emerging technologies is emergency response. Consider that unmanned ground, aerial, and marine vehicles have already been used for disasters starting with the 9-11 World Trade Center collapse and including Hurricane Katrina, civil engineers have begun embedding RFID tags in structures that can be interrogated post-disaster, and numerous companies have entered the mobile ad hoc network market offering easily deployed field communications systems.

Emergency response introduces a new level of environmental complexity in terms of heterogeneity, multiple spatial and temporal scale, uncertainty, resource constraints, distributed computing, and autonomy for CPS. It is a “wicked problem,” with large interdependencies, no single optimal solution, and nonlinear behavior. Individual robots require control, but the heterogeneous collection of such devices must be coordinated and controlled on a large geographic scale, both by on-site tactical and remote strategic communities. Emergency response introduces real-time deadlines, with both synchronous and asynchronous information updates and general uncertainty. Resources constraints such as power limitations and recharging opportunities as well as network bandwidth and available connectivity must be considered. Computing will be both distributed and centralized. Missions will most likely change as the disaster unfolds while changes in the environment might lead to surprises, both requiring rapid adaptation; thus the systems themselves must have greater levels of autonomy, authority, and adaptive capacity.

As we consider emerging CPS technologies such as unmanned systems and how to design and coordinate these technologies for emergency response, we have identified a new CPS challenge: **How can human expertise be integrated into cyber-physical systems to adapt and manage multiple, large scale, time critical processes?** Understanding the interaction between computational processes and the physical world with the overarching influence of humans will result in new and challenging problems in control. The computational processes in CPS usually consist of spatially distributed sensors and actuators observing and acting on an environment in a potentially inhomogeneous fashion; this presents unique challenges in the theory of switched, hybrid and embedded systems as a result of the concurrent nature of the physical world. Adding humans to the loop will further increase the need to address these challenges while simultaneously presenting new ones, e.g., environments necessarily introduce synchrony while the human element results in asynchrony. Therefore, strategies must be developed that can deal with discrete and continuous systems on multiple time scales in different time domains.

Incorporating the human into CPS benefits practical applications of robotics. Many domains such as emergency response and defense are adding technology that complements or extend human capabilities, but do not eliminate human involvement and decision-making as supervisors, partners, or general stakeholders. Robotic autonomy, while improving, remains low and in some cases decision authority must legally reside with a human; therefore mixed teams must work together in order to accomplish objectives. In the health and biomedical fields, robotic devices may share functions with humans, mandating a consideration of the human in the loop. Thus the human must be incorporated into, and indeed leveraged in, any general CPS framework.

Our general approach to tackling this challenge of human-CPS is to cast CPS within a novel polycentric control model. *Polycentric control models* are a new approach to adaptive governance for distributed activities, concentrating on the dynamic balance between multiple centers of control, each with partial authority and autonomy. They are different from traditional control in at least two ways. First, in contrast to the classic purely hierarchical command and control architecture where data comes from the bottom, decisions and control occur at the top with orders being passed down to the bottom layers, the polycentric framework incorporates both the horizontal (multiple sub-systems) and vertical (authority and autonomy at lower levels) distributions of control. Second, polycentric control does not concentrate on optimizing the fitness of the system at its different scales, as different researchers believe that focusing on improving fitness impairs the capacity of the system to adapt to surprising events. The focus on fitness often leads researchers to define a particular algorithm, machine or network of machines organized to fulfill a particular goal as the unit of adaptive behavior. Instead, the polycentric model considers three main classes that correspond to multiple scales in the system: an individual scale, where adaptations are cognitive; a distributed activity scale, where individuals or groups coordinate and synchronize their roles over time and space; an organization scale, managing pressures, high-level goals and resources. As a result of these differences from existing control approaches, a polycentric control model is better suited to manage common pool resources over multiple stakeholders, complexity and diversity, market design, and commander's intent in command and control. Note that our interest is not in inventing new modeling techniques but in orchestrating multiple modeling techniques to understand how such adaptive, reflective, multi-role, multi-center systems behave and to discover regularities.

One outcome of the polycentric control, adaptive governance philosophy is a shift from an “either-or” partitioning of autonomy between human and robot to cooperative autonomy, where roles can be traded but also shared, going beyond teleoperation. One goal is an information-theoretic expression of how roles and responsibilities are distributed and coordinated among humans in high-performing teams as compared to the unique constraints of human-robot teams. This *shared role formalism* for shared autonomy and human-robot interaction is expected to identify minimal conditions, especially communication, needed for coordinating different agent activities, anticipate vulnerabilities and lead to the more efficient use of constrained networking and allocation of computational resources.

Another aspect of this larger viewpoint is that it provokes a reconsideration of how existing methods such as machine learning can be applied. For example, most machine learning approaches in the literature place the intelligent learning agent in the inner-loops to learn local behavior, and the control element (usually a standard optimal controller) in the outer-loops to control global behavior. Our *hybrid machine learning/adaptive control* approach for unmanned aerial vehicles is the inverse, and uses an intelligent learning agent, which may be assisted by a human, at the highest level(s) to learn global behaviors of the coordinated heterogeneous system. The high level intelligent learning agent not only learns to respond to new situations, but also directs the lower level or local behaviors of the system, which are handled with an adaptive controller. Thus adaptivity to changing system characteristics at both global and local levels is a feature of this approach.

An important key to creating structures and principles for control is to consider *biological organization*. Biological systems are well-known for their ability to adapt within their ecology. Behavioral control of robotic and web agents has been long established through quasi-formal principles eschewing models. Advances in mathematical modeling of biological processes leading to adaptability, efficiency, and robustness suggest that it is now possible to create meaningful formalisms that can prove correctness and coverage. Existing behavior-based methods of robotic control may be extended to heterogeneous groups by emulating stigmergy, the biological process by which multiple agents coordinate actions to achieve common goals without explicit communication (examples of implicitly coordinated collective activities can include nest construction, environmental exploration and foraging/gathering). In emergency response, where heterogeneous teams consisting of human workers as well as various robotic agents must interact, explicit coordination may be difficult or intermittent, due to incompatible communication protocols or poor channel characteristics. Using only environmental cues (metrics of progress or "pheremone"-like signals), collective search and map construction functions can be developed.