

Cyber-Physical Systems: Position Paper CPS Environments

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Interactive mediation between the information world and the physical world is a key domain for innovation and a major challenge to building Cyber-physical systems. New approaches to how we interact with the worlds of information and cyber-observable reality whether it be global environment observatories, scientific experimentation, visualization, education, tourism, or entertainment require a combination of technologies akin to computer gaming, social computing, mobile and ubiquitous computing. In particular, the issues of representation, human-machine interfaces and metaphors, techniques to allow collaborations within scientific and cyber-physical related endeavors suggest radical rethinking of infrastructure, design and engineering.

A global environmental observatory provides one inspiration for how we would like to interact with data intensive Cyber-Physical Systems. Imagine instrumenting an Antarctic colony of penguins with video, location, sound, temperature, and wind sensors, and in future, chemical and biological measurements as well. Then imagine mapping that environment into a next generation scientific version of Second Life where scientists from all over the world can visit the colony as a cyber environment: attach tracing streamers to birds, analyze which birds meet, what bird calls correspond to what communication, and how the birds react to threats. Then imagine how such environments could be scaled up to encompass the solar system, or scaled down to reveal the inner workings of an Ant colony.

We see Cyber-Physical Systems as a part of a broad approach to data interaction and we propose the creation of an open source software infrastructure, a Cyber-Physical Environment, that will support this wider variety of interactions and applications. Much as the web supports a far wider community than the physicists originally imagined, so too, our proposed CPS environment will support communities that do not yet even exist.

Limitations of existing CPS. We draw lessons from earlier work in ubiquitous computing, digital libraries, cyberinfrastructure for science, and arts and entertainment. In all these areas, we see a critical gap between the emerging Cyber-Physical infrastructure and user environments. Existing CPS have not yet made the leap from one of a kind experiment to generally useful infrastructure. While there are many limitations that stem from this lack of generality, the most important are the lack of sufficient flexibility and modularity. As new capabilities and concepts become available, they should be easy to integrate into the CPS. The third major limitation, also arising from not addressing CPS generally enough, is not to envision the wealth of new and diverse users who would be drawn into a sufficiently general system and who therefore would need better support tools, simpler interfaces and a general order of magnitude improvement in ease of use.

Grand Challenges for Cyber-Physical Systems. The grand challenge for CPS is to create a generally accepted, extensible infrastructure that will support the widest possible variety and number of sensor inputs and display/actuator outputs, while simultaneously making the system easy to use for the greatest number of potential users. The challenge is not to create one-off

systems that are useful to 1% of the community and only understandable and usable by specialized scientists and technicians. Instead it is to provide an innovative cyber-infrastructure that is a general yet powerful system used and *useable* by the majority of the community. It should offer new ways for humanity to observe and experience, reason and reach decisions about the universe in which we live. The infrastructure should allow different cyber-physical systems to co-exist and interact within a familiar, navigable framework. It should allow the aggregation of human knowledge and skill to be combined with cyber-observation and manipulation of physical environments to make new realms of human creativity and experience. For example, it should not only be possible to create a cyber-physical observatory on Mars. It should be possible to link that observatory to many different scientific and educational projects, to allow public observation and tourism, to encourage public discourse, information dissemination, and debate.

Requirements of general purpose, flexible Cyber-Physical System. All cyber-physical systems “must be dependable, secure, safe, efficient and operate in real-time. They must also be scalable, cost-effective and adaptive.”¹ We believe it is important to extend this list of requirements in ways that will make them more generally useful and reach wider audiences. From our experience, we identify the following important requirements:

- 1) They should be open source and open, modular, and extensible in design.
- 2) They should allow for a wide range of operating conditions, from single user to massive communities of potentially simultaneous users.
- 3) They should allow experimentation from both developers and from a general public perspective.
- 4) They must support tracking and reporting facilities so that they can be used for experimentation.
- 5) They must provide clean experimental environments – ie, not ones messed up by adverts, roving lunatics, or hackers.
- 6) They must offer reliability, security and privacy if experimental results are to be valid. They need a very robust security model.
- 7) They must accommodate a variety of talents at creating and manipulating content: the target user base is very broad, including scientists, business people, artists, teachers, and students of all ages.
- 8) They must support repeatable experiments.
- 9) They should have a framework for measurements.
- 10) They should allow easy insertion of different or new representation engines (such as graphics renderers) and new and extendable data bases, etc.
- 11) They must have a robust, reliable, repeatable structure for action sequences and scripts.
- 12) There should be excellent debugging tools and scripting tools.
- 13) As much as possible, the tools should be hosted within the environment and accommodate collaborative users. That is, while viewing and manipulating data or moving through representations, you should be able to create new representations or processes without restarting or leaving the system.

Innovations, Ideas, Abstractions and Terminology for Cyber-Physical Systems. We propose an abstraction based on concepts and technologies adapted from massively multiplayer gaming

¹ <http://varma.ece.cmu.edu/cps/CFP.htm>

(virtual, or synthetic, worlds that can support thousands of cyber-physical or virtual objects and thousands of real-time interacting networked people). We propose building a generic (non-game oriented) toolkit providing easy to use data input modules, data visualization and actuator output modules, and simple one-to-one, many-to-one, and many-to-many human communication modules (including simple text chat, voice, collocated manipulation of virtual data objects, etc.). This tool-kit would offer cyber-physical system interfaces based on standards (for example, OMG's and W3's IDL, UML, UDL, XML) and integrate them into a standardized fabric for virtual worlds. To give but one compelling example, an instrumented "cyber-physical" International Science Park on Mars could be visited by the general public, inquisitive students could view the geology, chemistry, climate, and scientific activities in the park, remote scientists could conduct experiments from afar, and local "Martian" scientists would be free to conduct their science. The tool-kit would offer a multi-layered approach much like Geographical Information Systems that support rendition of different kinds of related data in mapping systems. Similar to such mapping systems, the virtual world technology would support fly through capabilities and 3-D visualization.

Milestones. Possible milestones for the next 5 to 10 years include:

1-2 yrs: uniform data exchange that supports real time acquisition and control

2-3 yrs: interface tools within the environment allowing for manipulation and multimodal display

3-5 yrs: open source framework available

5-10 yrs: widespread adoption

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² www.culturalcomputing.uiuc.edu