The Web of Things and Cyberphysical Systems: Closing the Loop

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Abstract

Many important applications of the Web of things are not limited solely to cyberspace; they involve the control of physical systems that include cyber components but whose behavior cannot be arbitrarily manipulated by software. Examples of cyberphysical systems (CPSs) include automobiles, factories, buildings, aircraft, and medical devices. The WoT has much to contribute toward overcoming the limitations of today's CPS control technologies and in particular to bringing advanced monitoring, control, and optimization to applications where conventional platforms for such capabilities are infeasible, for economic or technological reasons. However, closed-loop WoT applications to CPSs will require in-depth understanding of their dynamics, especially since poor performance and failures are not just an economic concern with CPSs—environmental and human safety are typically at stake as well. Expertise in control and dynamical systems and the engagement of the appropriate research communities will be essential for realizing the "real-world" potential of WoT.

From the Cyber to the Cyberphysical

I am interested in taking the Web of Things beyond the purely cyber realm; that is, beyond applications such as social media, gaming, financial services, online retail, intelligent search, and analytics. In all these cases, the coupling of the information, communication, and computation to the physical world is, in some sense, incomplete; the output of a WoT application isn't affecting "physics" directly and immediately.

In contrast, in cyberphysical systems (CPSs) information and communication technologies are inextricably integrated with physical systems. It is CPSs that make the things we need, that move us and our possessions, that ensure our environments are comfortable, that generate and distribute energy for our use, and that furnish the physical infrastructures which underpin modern societies. Most CPSs are also closed-loop systems, and it is through communication networks, computational elements, and algorithms hosted on the latter that the efficient, safe, and reliable operation of these CPSs is achieved. To take the example of an industrial process, literally thousands of sensors (in some cases one or two orders of magnitude more) periodically monitor physical parameters—e.g., temperatures, pressures, flows, material concentrations—that are communicated over dedicated networks (mostly wired but wireless sensors are being adopted, albeit slowly). Control algorithms process this data, also with a predefined periodicity, and their outputs are communicated over dedicated networks (less likely to be wireless) to actuators. Timescales of CPS applications vary widely. Process control is relatively slow, with sampling and control rates often on the order of minutes. On the other hand, powertrain control in automobiles—fuel injection, for example—can require millisecond control.

Control Systems for CPSs Today

The fact that our aircraft, cars, refineries, buildings, and medical devices function as well as they do is testament to the power and maturity of control science and engineering. But it's worth noting a few assumptions on which this success typically rests:

- Communication networks are generally assumed to be completely deterministic and reliable
- Real-time operating system platforms rely on static schedules for computation and communication
- Each CPS requires a dedicated, on-site end-to-end control system
- With limited standards and interoperability, vendor lock-in is commonplace

Some control is now occurring over the Internet, incidentally, but at a supervisory level—for power grid distribution stations, wastewater treatment plants, some commercial buildings, and other applications. The feedback control equipment, infrastructure, and intelligence are still localized.

What the Web of Things Promises for CPS Control

What could be done with control over the Web and Internet that is hard to do today? Use cases can be developed that illustrate capabilities such as the following:

- Systems that are not physically connected or collocated could be coordinated in real time
- Optimized performance (e.g., energy efficiency) could be achieved for small-scale systems that cannot afford dedicated control systems
- High-fidelity models could be widely applied for real-time control via cloud-based implementations
- Global networks of sensors and actuators could be implemented and coupled with sophisticated control and optimization algorithms
- Greater redundancy and fault-tolerance could be achieved across all CPSs

Two representative examples are discussed below.

Energy optimization for small- and medium-scale commercial buildings. A significant majority of large commercial buildings have full-fledged building automation systems (BASs), allowing sophisticated energy optimization and control algorithms to minimize electricity and fuel costs while ensuring occupant comfort and site productivity. On the other hand, hardly any small commercial facility and very few medium-scale ones can afford a sufficiently capable BAS or energy management system; most such sites have little more than programmable thermostats. The vast majority of commercial buildings fall into the small-to-medium-scale category. The Web of Things can level the playing field, allowing advanced control algorithms to be executed remotely based on building models that are developed remotely.

Coordination of vehicles for traffic management. Road traffic management is a manually intensive task today, involving operators and engineers looking at camera feeds and effecting ramp meters and variable speed limit signs—the state-of-the-practice manifests significant limitations to sensing and actuation capabilities. With telematics, these limitations can be overcome, and looking further ahead self-driving cars will present especially intriguing opportunities for closed-loop traffic management. With destination information available for vehicles along with congestion data, automated guidance and control could substantially reduce travel time, fuel use, and CO_2 emissions.

The Need for Cross-disciplinary Collaborative Research

To the WoT community, it may seem that (a) we have the infrastructure and technology already available to realize these envisioned capabilities, or (b) the evolutionary path of ICT enhancement will take care of limitations that preclude realization today. What belies such perceptions, though, is the fact that closed-loop control is not just, or primarily, an ICT challenge. Feedback can qualitatively change the behavior of a dynamical system, for better or worse. A seemingly benign system can become unstable if feedback is inappropriately applied—cf. historical instances of bridges destroyed as a result of resonance effects caused by synchronized marching of soldiers or wind disturbances. On the other hand, automatic feedback control enables unstable aircraft—that humans cannot pilot without automation—to perform high-performance agile maneuvers. Control scientists and engineers understand these issues, and the closed-loop integration of physical systems with WoT will require close collaboration of controls and dynamical systems experts with computer scientists and Web technologists.

A few examples of research issues with CPS operation via the Web of Things are noted below:

- *Control over nondeterministic networks.* Today's CPS control systems assume deterministic communication and computation—in fact the execution and communication infrastructure is rigorously designed to ensure determinism. Nondeterminism—e.g., in sensor reading, packet delivery, or processing time—complicates closed-loop performance and stability.
- *Latency and jitter.* Latency refers to the end-to-end delay from sensor reading to actuation. Latency can be inherent in the physical system itself (material flows through pipes) and is predictable in such cases. Jitter refers to variance in the intersampling interval (even if the average sample rate remains constant). Both latency and jitter can create challenges for closed-loop control and require the use of special techniques. This must be kept in mind with control over the Internet and cloud.
- *Bandwidth.* Many control systems are not demanding of communication bandwidth—a few sensor reads and actuator outputs a second can suffice. But where safety is at stake even this level of performance cannot be taken for granted (and may not be assured with mobile and/or Internet connectivity). Furthermore, closed-loop control with video feedback (and feedback of other high-dimensional data) will both demand and stress bandwidth; sophisticated video-processing algorithms will for most applications be best run on cloud platforms.
- *Interoperable and plug-and-play sensors, models, and algorithms.* WoT has the potential to become the first open platform for many CPS control applications. Benefits that have been

attained in other fields, such as discovery, search, and composition of services, could be extended to CPSs. Interoperability of components and software could be achieved. But interoperability will need to extend beyond the interface specification; "dynamic" compatibilities will also be critical.

- *Cyber- and physical security, and resilience.* Security for CPS also must encompass both cyber and physical elements, and the two must be considered conjointly. CPSs imply physical constraints that, if appropriately incorporated, can enhance detection and protection approaches. Conversely, physics and feedback can open the door to new attack scenarios: e.g., a well-performing control system can be rendered unstable by introducing small delays in communication pathways.

Research is already under way in the controls community in these and related areas. But a closer connection with the WoT community would be of mutual benefit and would accelerate the roadmap.

Next Steps

The suggested efforts and outcomes below should not be seen as strictly sequential; they can be pursued in parallel. They are intended also to suggest an evolutionary path to future applications.

<u>*Use cases and requirements.*</u> There are exciting opportunities for industrial and societal impact with WoT-based control systems. W3C can help prepare a library of these. With use cases documented, requirements for technologies and interoperability could be developed. A couple of examples have been sketched above, but these need to be elaborated and there are many more to be articulated. Many CPS systems are safety- and performance-critical. Assurance, even if probabilistic, will be needed before we can trust their operation to the WoT.

<u>*Test beds and pilots.*</u> We need to identify the right first demonstrations. Energy management for small/medium-scale commercial buildings is one good prospect. Others need to be identified. Initial test beds cannot be safety-critical. Indeed it seems implausible, at least today, that WoT will ever be extended to, say, flying an airplane through the cloud (speaking strictly metaphorically).

<u>*Semantic models, standards, and certification.*</u> Standardization and certification are prevalent across CPS systems today, but these are targeted for automation infrastructure and practices. In contrast to hardware devices and communication protocols, cross-vendor compatibility is rarely seen with optimization and control modules, dynamic system models, and other software-based components. In principle, the same control algorithm (i.e., the mathematical equations) can be applied to completely different industries; both simple algorithms such as proportional-integral-derivative (PID) control or sophisticated ones such as model-predictive control (MPC) are used for disparate applications. However, the software products are specific to industry sectors or subsectors. For WoT to help overcome this limitation, ontologies and semantic models will need to be developed that go beyond today's device and service models. In addition, certifications and QoS requirements will be needed that are relevant to closed-loop control (e.g., timing and throughput of Web services).

Concluding Remarks

In this position paper I have attempted to sketch what I consider a promising space for WoT technologies with the potential for dramatic enhancements in cyberphysical system design, performance, and cost-effectiveness. Collaboration between control scientists and the WoT community will be necessary. More than anything else, this paper is a call to encourage such collaboration.