Cyber-Physical Systems: A Confluence of Cutting Edge Technological Streams

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Abstract— **Cyber-Physical Systems (CPS), the complex closed-loop control system that operates by close coordination of the physical components and computational entities through networked communications, is an emerging technology with great application potential. Advances in networking, sensors, embedded systems, and computer hardware/software/ middleware technologies have enabled research in this area, but still many formidable challenges remain. Starting with an anatomical view of a CPS, this paper presents defining characteristics of a CPS, state-of-the-art in CPS research, CPS challenges, and opportunities for solving complex application problems.**

Keywords— **Cyber-Physical Systems, Closed Loop Control Systems, Embedded Systems, Sensor-Actuator Networks, Dynamical systems.**

I. INTRODUCTION

Fuelled by recent advances in sensor networks, wired and wireless networks, embedded systems, communications, computers, and control engineering, Cyber Physical Systems (CPSs) are finding their way into every facet of our lives from heath care [1]-[3] to national security [4]-[5]. According to Lee [6], a CPS is a system with its computational and physical processes well integrated. Though it appears, from this definition, that a CPS is a simple computerized control system, the CPSs turn out to be systems capable of solving very complex control problems in present-day distributed sensing and computation environments. Hence, we adopt in this paper a more comprehensive definition of Raj Rajkumar [7] of Carnegie Mellon University, and consider CPS as a system that integrates computation and communication capabilities with monitoring and/or control entities in the physical world.

We illustrate the concept of a CPS with an example problem of tracking a bio-chemical weapon being carried by a terrorist. The chemical plume from the mobile weapon will be sensed by various sensors in the surrounding region, and their measurements will be passed onto a central computer or various computers in the vicinity for identification and position estimation of the chemical weapon. The measurements may not be accurate because of the wind and other atmospheric conditions for non-homogeneous propagation of the plume in different directions. Some measurements could be incomplete because of occlusion problems. These problems are similar to those encountered in wireless communication. Further, because of the cheap sensors, inaccurate or faulty measurements are possible. Thus CPS is a complex closed-loop control system that makes use

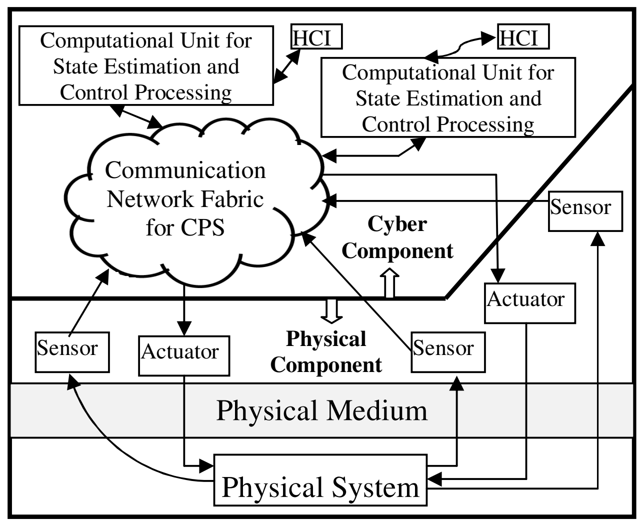

Fig. 1 Nuts and Bolts View of a Cyber-Physical System

of inaccurate or incomplete data from sensor networks to make intelligent control decisions to operate the actuators for effective control of physical processes. Here the physical process dynamics and related senor measurements define the physical component of a CPS whereas the communication, computation, and control aspects define the cyber-component. The word "cyber," which originated from the word "cybernetics," naturally refers to networked communication, computation, and control.

II. NUTS AND BOLTS VIEW OF A CPS

Fig. 1 presents a nuts and bolts view of a CPS. As indicated in the introductory section, a CPS consists of a cyber component and a physical component. At the core of the cyber component is the communication network fabric that includes sensor networks for communication between the sensors and computational units, and the INTERNET with the wired or wireless computer subnets for communication between the computational units and actuators for controlling the physical system. The computational units perform the heavy duty computing for estimation of the system state (e.g. location of the biochemical weapon and the direction of its movement) and generation of appropriate control signals for the actuators. The human-computer interfaces (HCIs) permit the humans to take overriding control decisions based on state estimates and thereby become a part of the CPS. The physical component of a CPS includes the entities that are closer to the physical system under observation e.g., sensors that take measurements related to the physical system dynamics (e.g. intensity of the chemical plume at particular locations), and the actuators that affect the physical system or its dynamics.

Even though Fig. 1 depicts a logical separation of the entities belonging to the cyber and physical components of a CPS, it is possible that these two types of entities are co-located in a real world situation. For example, an embedded system for control processing may be a part of actuator hardware. Similarly, in some cases as the aforementioned plume tracking problem, there could be an intervening medium (air or water) between the physical system and the sensors/actuators, and signal distortions can occur based on the atmospheric conditions. Thus the physical medium here behaves almost like a wireless communication medium, and hence be categorized as an entity of the cyber subsystem. In the other cases such as remote guided surgery where sensors are close to the physical entity, the signal distortions can occur in the communication medium between the sensors and computational elements. With recent developments in embedded systems, it is also possible to integrate sensing and computational elements, and implement a CPS in a distributed computational-control environment.

III. CPS Characteristics

Though the sensor-actuator networks, embedded/real-time systems, desktop/laptop computers constitute a CPS, none of them could exclusively be considered as a CPS. As indicated in [6], CPS is a dynamically reorganizing and reconfiguring control system with high degree of automation, complexity at multiple spatial and temporal scales, and control loops closed at all scales. They are also systems with entities networked at multiple scales possibly with cyber capability at each physical component and dependable and certifiable (secure) operations. In short, high degrees of complexity and tight coupling and coordination between system's computational and physical entities through networked communication characterize cyber-physical systems.

IV. State-of-the-art in CPS Research

Even though the systems with different CPS components such as sensor networks, controllers, actuators, distributed computers, etc. have been in use in various applications for some time, the integrated whole called CPS has become a focus of attention only recently, possibly after the US National Science Foundation (NSF) workshop on CPS [7] and hence **CPS** may be considered as an emerging discipline of research [3, 8].

Recent flurry of activity in CPS research has resulted mostly in conference publications. The research papers in the CPS area may be categorized into five groups based on the following themes:

i) **Specific Applications**, *e.g.,* national defense [4]-[5], space exploration [9], manufacturing [10] and concurrent control of several industrial plants [11], road traffic management [12], energy systems [13], [14] and power infrastructure [15], healthcare (monitoring devices [1], and tele-surgery [16]-[20].

ii) **CPS Challenges and Opportunities** e.g., [3], [21]-[22]

iii) **Methods and Tools:** Papers under this theme address in a CPS context various traditional issues related to computers and networking including system resilience [23], robustness [24], data reliability [25], fault-tolerance [26]-[27], and security [28]-[31].

iv) **Components, Runtime Substrates, and Systems:** The focus here is on various hardware and software issues that include high performance control-computing co-design [32], real-time environments [33]-[34], service/task scheduling [35]-[36], real-time middlewares [2], [37]-[38], and specification logic [39].

v) **Foundations:** Among the many papers found in the current CPS literature, the paper Illic *et al.* [13] can be categorized under this theme also. This is the only one with this theme among the papers surveyed. But, since the model proposed therein is very specific to future cyber physical energy systems, it may not be considered as a generic CPS foundational work.

V. CPS Research Challenges

Some of the CPS research challenges are:

- Progress in CPS research can only be accomplished through the development of underlying technologies such as embedded systems design, new software/hardware verification and validation paradigms, safety critical designs, control theory and systems design, sophisticated human-computer interfaces that permit quick human intervention, sensor-actuator network technologies, secure communication, network protocols, and cross-layer designs for real-time operations, and so on.
- With the development of underlying technologies, there will be an urge for sophisticated safety/security-critical applications that provide high degree of automation and real-time performance.
- Complex applications demand complex solutions involving heterogeneous (analog or synchronous/ asynchronous digital) distributed systems and novel digital control algorithms. Heterogeneity here implies the systems could be either analog (usually, actuators and physical systems) or synchronous digital and event-triggered (asynchronous) systems for control processing.
- CPS requires paradigm shift from centralized control systems to decentralized event-triggered control systems

that operate at multiple scales and have the capability to reorganize and reconfigure.

- The complexity of CPS design demands the use of new system models/analytical tools, and software simulation tools. Currently the modeling of physical system dynamics can be done by differential or difference equation based on whether continuous data (analog) or sampled data (digital) control systems are being used. A lot of mathematical (analytical) models such as state vector formulations and Lypunov functions are available for control system design. Software tools like MATLAB-SIMULINK, LABVIEW, SCADE, Statemate, etc. are available for design of traditional control systems. But none of these models or tools scale up for the CPS design. There is a dire need for addressing this area of research.
- Complexity of CPS also demands new automated test tools that reduce test and system integration costs.
- Tradition control systems (e.g. break controls) work based on the input command signals, whereas the CPSs need to be equipped with intelligent control. Sophisticated CPSs should also be able to guess user intent from the context.

VI. CPS OPPORTUNITIES FOR ADDRESSING GRAND TECHNOLOGICAL CHALLENGES

In industry round table on CPS at NSF on May 17, 2007, Rajkumar identified the following technological challenges that could be addressed by the CPSs:

- Effective traffic control with significantly low congestion and delays, and zero fatalities and minimal injuries in traffic accidents
- Effective power grids with real-time cooperative control of protection devices, and self-healing (re-aggregated) islands of bulk power that facilitate blackout-free electricity generation and distribution.
- Critical physical infrastructures that call for preventive maintenance
- Access to world class medicine from anywhere anytime
- Energy-aware buildings
- Effective agriculture with high crop yield
- Life aides to older or disabled people

In addition to the above, the CPS technology can also be used in the following challenging applications:

- Border security
- Surveillance of Terrorist or criminal activities and real time notification.
- Remote guided surgery
- Medical implants that use feedback from natural healing processes
- Highly tolerant aerospace and avionics systems
- Highly automated manufacturing systems
- Deep sea exploration, firefighting, and other hazardous operations

VII. SUMMARY AND CONCLUSION

In this paper, we present characteristic features and constituent entities of cyber-physical systems. We also present an overview of the current research in this emerging discipline, CPS research challenges, and the opportunities this research provides for the solution of most intricate problems. At present, most papers in this area are position papers in conferences or magazine, but it is likely that more technical papers in archival journals will appear with the progress of research in this area.

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