Chapter XX

Cyber Physical Systems and Technologies for Next Generation e-Learning Activities

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This paper discusses the importance of cyber physical systems (CPS) and their potential for supporting interactive learning in distributed e-learning contexts. Recent advances in Internet technologies will provide a foundation for the creation and adoption of innovative learning approaches which enable students to access, interact and learn using both cyber (software) and physical tools, systems and equipment. Fundamental concepts related to educational CPS are proposed and discussed along with a general framework for such educational activities. The key technological and educational challenges are also elaborated.

INTRODUCTION

Recent advances in information technology (IT), including next generation networking technologies, hold the potential to change the face of educational approaches at both the K-12 and university levels. Virtual Reality technologies and environments along with other computer based tools and approaches are gradually being introduced to teach engineering and science concepts in universities and schools [1]. A related genre of tools and systems termed as 'cyber physical systems' are becoming the focus of research efforts which hold the potential of substantial advances in the way in which engineering and other systems can be designed and implemented. In this paper, we discuss some of the fundamental concepts and characteristics of such cyber physical systems and technologies and subsequently highlight their importance in developing next generation educational approaches in engineering.

Cyber systems are computer-based or software systems, environments and tools used in a variety of engineering, science and other domains. Physical systems (as the term implies) refers to an integrated set of components and equipment which accomplish a targeted set of objectives ranging from manufacturing a set of parts, to monitoring physical activities, to other physical engineering tasks (such as measuring dimensions as part of quality control or remotely controlling an unmanned aircraft). Physical non-engineering tasks can also be accomplished by such physical systems including monitoring the condition of plant crops in an agricultural field to meteorological assessment of a specific region, among others.

A cyber-physical system (CPS) can be described as a system of collaborating computational elements controlling physical entities [2]. Today, embedded systems can be viewed as a pre-cursor generation of cyber-physical systems which can be found in various fields including manufacturing, healthcare, and transportation. CPS can be viewed as a collaborating network of interacting components with physical inputs and outputs [3].

In the context of cyber physical systems (CPS), there have been a limited number of papers focusing more on the research aspects than the educational potential of CPS systems and technologies. An overview of CPS research is provided in [4] including a review of theoretical results on modeling and analysis of dynamic behavior of CPS. The importance of the three key properties of CPS include safety, security and sustainability is highlighted in [5]. The authors have presented a theoretical framework for cyber physical interactions which facilitates systematic design to ensure the adoption of these 3 properties. This framework is discussed using examples from various domains including data centers and unmanned aerial vehicles.

Other CPS applications can involve use of sensors to monitor and provide feedback from a target environment to a centralized node; use of such a sensor based feedback approach has substantial potential in distributed robotics, medical monitoring, and advanced manufacturing. A review of literature indicates only few implementations of cyber physical systems. One such application is MIT's Distributed Robot Garden where a group of robots services a garden [6]. The plants in the garden each has sensors to help monitor and control the interactions. Another application involves calculating fastest routes for taxis in Boston based on traffic information [7]. In [8], a cyber physical test bed for assembly of micro devices is discussed where virtual and physical tools are used to assemble target designs.

In [9], the design aspects involved in a typical cyber physical system beginning from computational modeling until implementation are discussed. The simulation of an Unmanned Air Vehicle (UAV) Application is discussed as a case study. The results indicate the efficiency of the modeling and analysis activities; however, the authors note that with a real physical test bed, sensors may not function normally as assumed in the simulation.

Service Oriented Architecture (SOA) systems and Cyber Physical Systems are two related technologies viewed by researchers as key to improving the sustainability of industrial systems [10]. In [10], a real time service oriented architecture (SOA) is outlined to support sustainability and predictability in cyber physical systems. A real-time middleware is proposed to build the support for service accountability and resources managements for service processes. In [11], the heterogeneity of components and interactions is viewed as a unique challenge in the integration of cyber physical systems. The authors emphasize that that this heterogeneity underlines the need for modeling and analyzing across domain interactions, which includes developing a new foundation that is more model-based and predictable.

Cloud-based computing provides an innovative way to store and share cyber resources which can be accessed from geographically distributed students, educators and other users. Cloud computing [12] is a model for enabling ubiquitous network access to a shared pool of resources (including networks, storage, services and servers). Some of the benefits for cloud-based manufacturing include reducing up-front investments and lower entry cost (for small businesses), reduced infrastructure costs, and reduced maintenance and upgrade costs [13, 12]. In the later section of this paper, a cloud-based cyber physical system for assembly of micro components is discussed.

COMPONENTS OF EDUCATIONAL CYBER PHYSICAL SYSTEMS

In this section, the concept of an educational Cyber Physical System (ECPS) is proposed and discussed for next generation learning and education. An ECPS can be described as an integrated set of cyber physical components which support and enrich educational activities in engineering, science and other fields. An ECPS can be a localized system involving software (cyber) and physical (experimental) resources or can be a more advanced distributed collaborative system. The latter relies on advanced networking technologies that enable resources and components from geographically distributed locations to collaborate as part of educational activities aimed at specific learning objectives.

The essential components of a framework to support educational activities involving cyber physical systems and technologies can include:

1. Cyber components for students to interact with as part of their educational activities; examples of these can include design tools, planning tools and simulation environments.
2. Interface components: They enable the cyber components and resources to interact with their corresponding physical resources and lab equipment including robots, CNC machines, assembly work cells, etc.
3. Physical components: These can be viewed as the downstream actuation resources which support the completion of learning activities through experiments, manufacturing tasks (such as assembly of a proposed design) and other activities.
4. Feedback or monitoring components: A critical set of components whose function is to monitor the progress of physical activities and provide feedback to the cyber components and students interacting with them. These feedback components can include an assortment of sensors and devices including cameras, bar code readers, RFID and other equipment. For example, when a robot is accomplishing a given assembly task, cameras and sensors can provide

real time feedback about the work in progress as well as report problems encountered during the accomplishment of such activities.

5. Next Generation Networking capabilities: These are the most essential of the various components as they provide the networking capabilities for students and educators to interact, explore and exchange high gigabit data and information from distributed locations. Technologies based on cloud computing, ultrafast networks and software defined networking will play a key role in the creation of both educational and industrial cyber physical systems.

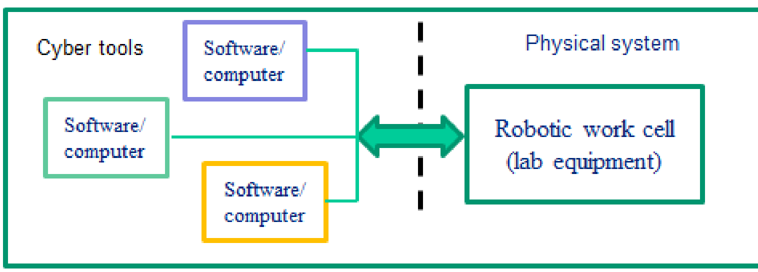

FIGURE 1
A LOCALIZED CYBER PHYSICAL SYSTEM WITH SOFTWARE TOOLS INTERACTING WITH A ROBOTIC ASSEMBLY WORK CELL (EQUIPMENT)

As shown in Figure 1, in a localized ECPS, the software tools which are part of the cyber resources can interface with a robotic assembly system or environment which is co-located in the same room or laboratory. Figure 2 illustrates a more advanced cyber physical system and framework in which an assortment of cyber (software) tools can be accessed by users from different locations; these cyber tools can also interface with a range of physical equipment either at one location or different locations. The cyber resources can be integrated through networking protocols including emerging cloud technologies.

In terms of stakeholders in such an ECPS, the key players in such a framework include the educators (who can be viewed as the educational service providers servicing the students), the CPS designers (who design the CPS for educational activities), the CPS builders (including the engineers and IT staff who develop the software tools and the design/develop/maintain the Internet technologies), the users or students (who access the CPS for educational activities) and the service personnel (who maintain the educational CPS to ensure its safe functioning on a day-to-day basis).

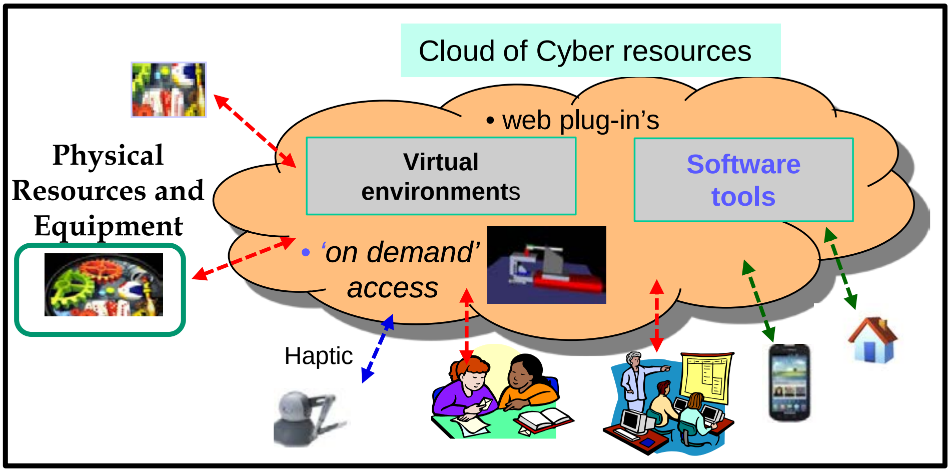

FIGURE 2
A DISTRIBUTED CLOUD BASED CYBER PHYSICAL SYSTEM

The networking capabilities for cyber physical systems can vary depending on the educational context and application. A brief overview of Internet2, the GENI initiative and the US Ignite project are provided to highlight the emergence of these next generation technologies. Currently, apart from the Internet, a limited number of universities worldwide also use Internet2. Internet2 has been developed to support advanced network applications and technologies, including substantial increase in the bandwidth which can be used to link hospitals, research labs and other institutions. For contexts such as remote surgery where real time data need to be exchanged, Internet2 provided an initial advancement over the Internet [14].

Two other major initiatives including the GENI project and the US Ignite need to be discussed as they pave the way for the design and implementation of educational and engineering cyber physical systems.

The GENI initiative is an NSF initiative [15] in the US which focuses on the design of the next generation of Internets including the deployment of software designed networks (SDN) and cloud based technologies (as part of a long term Future Internet initiative). In the context of engineering education, such networks will enable students and educators to exchange high bandwidth graphic rich data (related to simulation, Virtual Reality based modeling and analysis, physical monitoring of lab based activities such as robotics assembly in a work cell, etc.). GENI type Internet frameworks also hold the potential for engineering faculty to become partners in a global e-learning community where cyber resources (from lab modules to simulation-based resources) can be shared using cloud computing technologies which can require ultrafast high gigabit capabilities. In the European Union (EU) and Japan (as well as other countries), similar projects involving creation of Future Internet activities have also been initiated; in the EU, the Future Internet Research and Experimentation Imitative (FIRE) is supporting creation of engineering and computer science applications involving new networking and service paradigms [16].

With original inspiration from the White House Office of Science and Technology Policy and NSF [17], the US Ignite initiative seeks to foster the creation of next-generation Internet applications that provide transformative public benefit using ultrafast high gigabit networks. The six national priority areas are Advanced Manufacturing, Health, Public Safety, Education & Workforce, Energy, and Transportation. Both the GENI and Ignite initiatives herald the emergence of the next generation computing frameworks which in turn have set in motion the next Information Centric revolution which is expected to impact global educational practices. In the context of education (and cyber learning), such emerging networks will enable students and teachers to access learning environments (such as VLEs), software tools and cyber physical resources (from global locations through thin clients).

Cloud computing is another technology which promises to enable educators and students to access and share resources without having to worry about the maintenance of the applications [13, 1]. A key characteristic of using cloud computing technologies is that students with limited computing capabilities do not need any processors to access and interact with the cyber physical learning environments. As shown in Figure 2, the students can access a cloud of cyber or software resources, which in turn can interface with a variety of physical equipment including lab resources and educational work cells at different locations. Such an e-learning framework will enable universities as well as K-12 schools to share resources regionally and globally.

EDUCATION CPS FRAMEWORKS AND POTENTIAL IMPACT ON ENGINEERING AND STEM EDUCATION

Educational CPS frameworks and technologies will extend the current e-learning avenues and bring into play a number of technology based capabilities which were not feasible a decade ago. A brief overview of some of these innovative learning approaches and technologies is provided below.

Haptic interface-based learning environments and technologies refer to tools and virtual learning environments in which an user or student can touch and feel objects within a computer using appropriate interfaces. Studies with engineering students indicate that haptic augmented simulations were more effective in helping engineering students learn while making the instruction more engaging [18]. For example, using a haptic device, a user can feel the surface/texture of an object, feel the impact of forces coming into play during a virtual experiment, etc. Currently, a haptic interface works well in a co-located context where a student or user’s haptic device is linked to the target computer model (Figure 3A). With the emergence of the next generation Internet technologies, there is the potential to create virtual learning which can be accessed from a student’s home, dormitory or another location globally.

Another innovative class of environments are Virtual Learning Environments (VLEs) where students interact with 3D environments to explore engineering and science learning [1, 8, 19-22]. VLEs are virtual reality based environments created and used for educational and learning contexts where students can either learn individually or in groups to propose ideas, compare proposed alternatives and study their engineering impact virtually. Such simulation environments (Figure 3 B) can be linked using next generation Internet technologies which will enable teams of students from different locations to work together as a group as well as enable these simulation environments to

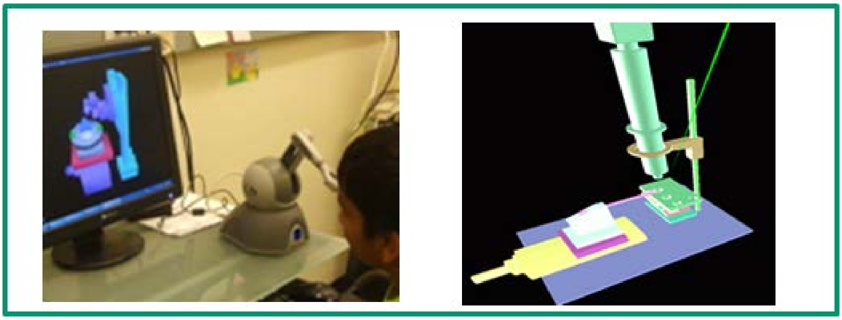

FIGURE 3
(A) STUDENT EXPLORING ROBOTIC ASSEMBLY CONCEPTS USING A HAPTIC DEVICE LINKED TO A VIRTUAL LEARNING ENVIRONMENT (LEFT)
(B) A VIRTUAL REALITY BASED LEARNING ENVIROMENT FOR ROBOTIC ASSEMBLY (RIGHT)

link to corresponding physical lab equipment; students can initially propose and validate their engineering solutions to a given problem (for example, developing an assembly plan using a specific robot and work cells) and then subsequently download their plans to physical equipment where the target assembly or task is accomplished. The progress of the physical activities can be monitored remotely by students in geographically distributed locations.

A cyber physical system for advanced manufacturing has been built at Oklahoma State University [23]. This CPS focuses on the assembly of micro devices using an array of cyber (software) modules along with physical micro assembly work cells. The cyber resources are stored on a cloud which can be accessed from different locations; these resources include an assembly planning module, virtual reality based assembly analysis modules, a 3D path planner, an assembly instructions (code) generator, among other modules. The physical resources can be interfaced after a given assembly plan has been validated; multiple partners at various sites can follow the simulation as well as assembly analysis through a cloud based framework. Finally, the target micro devices are assembled using physical micro assembly work cells; their activities can be monitored through cameras and shared with other users through the cloud based framework. Such cyber physical frameworks for advanced manufacturing can be used for educational activities as they enable the harnessing of distributed collaborative resources; multiple universities and industry partners can share their resources using cloud technologies within the context of cyber physical frameworks; such use of software and physical laboratory resources will not only help engineering students learn more effectively but also enable K-12 students to learn science, math and other STEM (that is, Science Technology Engineering and Mathematics) concepts from their homes and other locations. Such innovative approaches will substantially improve the access to educational resources for students in rural areas not only in industrialized countries but also in developing countries.

CHALLENGES IN ADOPTING CPS FRAMEWORKS AND TECHNOLOGIES

The primary challenges in the adoption of such next generation CPS frameworks and technologies include higher initial cost, access to next generation Internet technologies, safety and IT expertise to develop and maintain such cyber physical systems. Other challenges related to modeling dynamic abstractions in CPS as well as being able to manage a heterogeneous mix of sensors and actuators.

The first major challenge is the higher initial cost for universities and schools in investing in equipment which will enable them to ‘hook up’ to the emerging next generation or future Internet. Although they are not formally referred to as Internet3, these future Internets (plural) are being designed to be radically different from the current Internet in the way they function and in terms of the gigabit exchange capabilities. This initial cost is related to the next challenge which is to provide increased access to these ultrafast high gigabit networks. Universities in developing countries have lesser opportunities to access these next generation networks. A step-wise progression to these ultra-fast networks is necessary where initial funding is obtained from forward thinking educational foundations (such as the Bill Gates Foundation, Google and other IT powerhouses which are beginning to fund educational activities in developing countries). Federal agencies in the U.S., Europe, Japan and other countries are beginning to invest in these technologies to offset the higher cost involved.

Addressing safety concerns and issues is an important challenge in the evolution of CPS frameworks for educational activities. When students access physical systems from remote or distributed locations, it is essential to have a well-developed safety system which is integrated into the cyber physical framework. For example, students interacting with a robot assembly system may encounter unexpected problems where a robot malfunctions or there is a sudden break in electric power; such problems may result in accidents as well as cause physical damage to the physical equipment interfacing with the cyber modules being used for such cyber physical learning activities. The role of monitoring and safety sensors and modules becomes important in addressing such unexpected situations and avoiding accidents and related incidents [9].

Another key challenge is the expertise involved in the design, development and adoption of such CPS frameworks for educational activities. The CPS team intending to embark on such activities needs to include the educational experts (with the curriculum and pedagogical expertise), the engineers designing the cyber – physical environments (including the cyber or software modules, the engineering lab equipment to be used, etc.) and the IT personnel with expertise in next generation networking including GENI frameworks, ultrafast networking and cloud computing.

Allocation of resources as well as developing maintenance plans is crucial to the long success of such educational CPS frameworks. A well-developed safety plan also needs to be developed taking into considerations various scenarios for dealing with problems which can detrimentally influence safety concernsActuators, sensors (such as in cell phones) and sensor based networks can be used as a foundation for developing new CPS infrastructure [24]. However, new abstractions will be required which allow grouping of a heterogeneous mix of sensors and actuators from various networks and domains as well as for managing these groups. Cyber Physical Systems can be highly dynamic in nature in terms of the physical processes and computing resources. During runtime, the availability of the various entities can change substantially due to a number of reasons including mobility, noise, failures, etc. The supporting network layers for such systems can be unstable. Current network middleware are not designed to handle such dynamic aspects of CPS. In [25], a middleware architecture called Real-time Data Distribution Service (RDDS) is discussed which enables timely and reliable sensor data dissemination under unpredictable CPS environments. Performance evaluation results indicated that the integrated control loop provides robustness against unpredictable changes in workloads.

CPS software is usually built using programming abstractions with little or no temporal semantics. In [26], a programming model called PTIDES is outlined that serves as a coordination language for model-based design of distributed CPS. In [27], the challenges of modeling CPS is emphasized including heterogeneity, concurrency, and sensitivity; a part of an aircraft vehicle management system (VMS) to highlight these challenges. In [28], the need to develop methods and tools for design and analysis of CPS is emphasized. The key features identified include being able to support heterogeneous applications, scalability and mobility support and facilitating formal verification of physical interactions.

CONCLUSION

This paper outlines the emergence of next generation cyber physical frameworks which can support the adoption of next generation educational approaches and activities. An overview of fundamental concepts and characteristics of such systems was provided along with a framework for building such educational CPS systems. A discussion of next generation Internet initiatives including GENI and US Ignite was also provided. A summary of the key challenges in the adoption of educational CPS was outlined.

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