CPS Laboratory-as-a-Service: Enabling Technology for Readily Accessible and Scalable CPS Education

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***Abstract*—Future generations of cyber-physical systems (CPS) engineers and scientists must be ready to tackle the increasingly complex problems facing society. While it is possible for these students to gain a theory-based CPS education from the growing CPS scientific literature, we believe, however, that theoretical understanding alone is not sufficient particularly when CPS involve complex interactions between the cyber, physical, and sometimes, human realms. When coupled with practical hands-on CPS education, students will be able to experiment with realistic situations, which will better enable them to engineer high confidence CPS of the future. Unfortunately, there continues to be a dearth of readily available experimental CPS laboratories, which means that the graduating students remain unprepared to handle the monumental challenges facing society. To address this urgent societal need, we present CPS Laboratory-as-a-Service (CPS-LaaS), which leverages the principles of cloud computing, resource virtualization, and analogous systems that together enable CPS laboratories to be offered as a service on massive scales while eliminating the need to provide in-house laboratory resources at each institution. As a concrete example, we present Composable Conveyor System (CCS) as a sample playground for CPS experimentation and discuss the education opportunities for CPS experimentation in this concrete example. A key outcome of designing CPS-LaaS is an expectation of significant new scientific discoveries in the CPS realm.**

***Index Terms*—Position paper; Practical CPS education; ABET outcomes; cloud computing; virtualization; analogous systems;**

I. Introduction

Cyber-physical systems (CPS) pervade several application areas of societal importance, such as advanced manufacturing, transportation, health care, smart grids, and smart buildings. In all these areas, CPS techniques bridge the gap between the cyber and physical realms to manage the complex interactions and integration between these two realms. New CPS applications are either emerging or need to be developed to handle the significant challenges facing the society, such as dwindling natural resources, greenhouse emissions, rising healthcare costs, increasing population of the aged, traffic congestion, tapping into renewable sources of energy, and improving safety and efficiency in all means of travel modalities.

To address these challenges, we need our future scientists and engineers to be well-trained in the science and engineering of CPS. It is only now that some scientific results and engineering design ideas for CPS based on research conducted over the past five years are beginning to appear. A significant amount of additional work remains to be done, which will enable us to build a strong CPS workforce for the 21^{st} century.

It has been amply demonstrated that problem- and project-based learning environments help students apply learned theories to solve realistic problems, thus promoting deeper understanding of content knowledge as well as critical thinking and problem solving skills that transcend individual domains [1]–[4]. Thus, the CPS community must strive to create a problem-based learning approach to help students gain a better perspective on design, analysis, and verification, monitoring, and control through hands-on experiments in CPS laboratory environments.

Unfortunately, a vexing problem that makes it hard to support a problem- and project-based CPS learning environment stems from a general lack of access to fully equipped laboratories that can provide hands-on, practical CPS education to a large pool of future scientists and engineers. Today, only a select few universities are capable of installing and equipping laboratories for CPS education, and moreover, only a handful of academic groups have access to large testbeds to develop and experiment with new CPS ideas. Many reasons can be attributed to these limitations including the cross-disciplinary nature of the CPS domain, high procurement and maintenance costs, limited availability of funds to support such laboratories, a lack of technical expertise, and other logistics reasons, such as lack of space or the need to travel long distances to avail of existing testbeds.

The result is that the graduating CPS scientist and engineer ends up obtaining a theory-based understanding of the subject matter but often lacks solid, practical and hands-on training to begin tackling real-world problems after gradaution. This in turn is detrimental to meeting the desired ABET program outcomes and thereby in preparing the workforce to address the monumental challenges facing society. Many questions thus remain unresolved. For example, how will these students acquire the ability to study and understand real-world CPS, and then build analytic models of physical and cyber systems, and their composition? How will they be able to design and conduct simulations and tests of a cyber-physical system and meaningfully analyze the results? How will they be able to apply good engineering practices in the design of a system that mixes cyber and physical components subject to constraints including safety, security, cost, and dependability? How can they identify, formulate, and solve engineering problems that have both cyber and physical aspects?

To overcome this problem we present a framework called *Cyber Physical Systems Laboratory-as-a-Service (CPS-LaaS)*. CPS-LaaS will provide easy and affordable access to CPS laboratory artifacts over the Internet by virtualizing the physical CPS laboratory resources and offering them as a service in much the same way as contemporary Software-as-a-Service (SaaS) offerings in cloud computing [5]. CPS-LaaS addresses the community need for educational tools, testbeds and benchmarks. By virtualizing laboratories, CPS-LaaS will support a set of canonical projects that are easily replicable. By enabling students with readily available access to CPS laboratories, CPS-LaaS contributes to multiple ABET program outcomes.

The rest of the paper is organized as follows: Section II describes the architecture of CPS-LaaS; Section III describes its use in promoting CPS education; Section IV describes how CPS-LaaS can be used in massively open online courses on CPS; and finally Section V offers concluding remarks.

II. CPS-LaaS: Architecture and an Example Concrete Realization

Our concept of the Cyber Physical Systems Laboratory-as-a-Service (CPS-LaaS) is illustrated in Figure 1; the main idea in this concept is the notion of an *Analogous System* [6], [7] that is shown in this figure as the *Physical Infrastructure Layer*. This analogous system is essentially a functionally equivalent system that can represent the cyber and physical interactions of a class of CPS applications. For example, consider a student investigating coordination algorithms for a cluster of spacecraft. Since it is hard to access a laboratory with spacecraft, it is possible to approximate the spacecraft CPS by an analogous system comprising a cluster of robot blimps whose positions and trajectories can be controlled to mimic typical operational situations that confront the cluster of spacecraft. The robot blimps may also serve as an analogous system that is used to investigate coordination mechanisms for a planetary scale underwater monitoring system.

The CPS-LaaS framework we present solves two problems: (1) present purposeful abstractions of the analogous system to scaffold learning for a large number of users (shown as the *Virtualized Laboratory Layer* in Figure 1), and (2) offer large-scale virtual systems that can be operated in the cyber-environment by virtualizing a smaller-scale system that is easy to deploy, operate, and maintain. This latter aspect is shown as the *Laboratory as a Service Virtualization Layer* in Figure 1. In both cases, a CPS laboratory is offered as a web-based service to researchers and students. While this solution will enable students to develop hands-on experience in interacting, operating and maintaining CPS applications, the problem offering remote experience to deploy and commission CPS applications remains to be addressed. Nevertheless, the notion of analogous system is important and useful because the physical infrastructure can be reconfigured easily to systematically address the learning needs of students. Experiments that are set up by the user in the virtual layer will be mapped by CPS-LaaS onto the analogous system where the experiments will be conducted, and results will be appropriately transformed back to use the semantics of the virtual CPS layer.

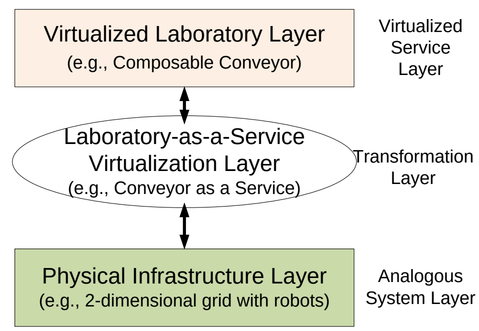

Fig. 1. CPS-LaaS Architecture

Our current work is focusing on one of many possible concrete realizations of the CPS-LaaS concept. The physical layer comprises a collection of mobile units that is called the Composable (or Cloud) Conveyors Systems (CCS) [8]. This is an analogous system that is well-structured and admits rich cyber-physical interactions. Users can specify and operate composable conveyor systems that comprise two kinds of units such as the ones described in [9]; some of the domain abstractions that are necessary and a method for transforming the virtual systems to the physical infrastructure is presented in [10]. Collectively, we aim to offer a virtualized CPS laboratory that minimizes the complexity and cost of design, operation and maintenance.

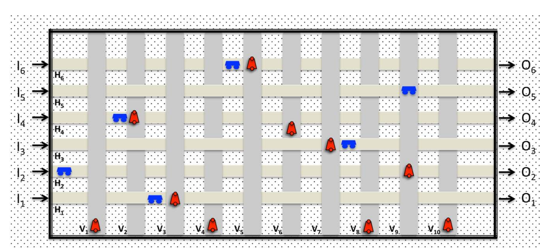

Fig. 2. Analogous System: A collection of mobile units move along fixed horizontal and vertical tracks in a periodic manner.

The physical laboratory comprising the analogous system used to generate the behaviors for the virtualized composable conveyor laboratory will comprise a system of inexpensive, computer controlled robots (*e.g.*, LEGO robots) that move along a two-dimensional grid as shown in Figure 2. Robots in the vertical lanes can move only North-South, while the robots in the horizontal lanes can move only East-West. Vertical and horizontal intersection lines of the grid will have two different colors so that the robot's light sensor can detect when the robot enters an intersection from East-West or North-South. The LEGO robots will be able to communicate with one another wirelessly, say, using NXTBee sensors that use XBee 802.15 communication protocol. Thus, these mobile robots that are simple to design, operate and maintain can represent many of the cyber physical interactions that arise in composable conveyor systems but at a fraction of the cost.

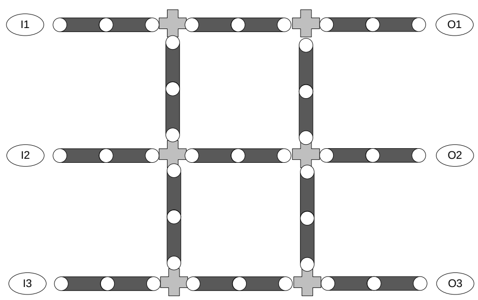

Fig. 3. Composable Conveyor Virtual Laboratory

As shown in Figure 3, users of this virtualized laboratory will be presented with appropriate building blocks to experiment with the system. For example, the figure shows an example layout of a conveyor system put together by students using building blocks, such as inputs, outputs, segments, and turnarounds. CPS students may then set the rates at which parts arrive in the system. They may define different types of parts that are handled on the conveyor. They may also add the logic of switching the parts at each turn unit.

III. CPS Education using CPS-LaaS

To enable a problem-based learning approach using CPS-LaaS, we are developing educational wrappers that support formal and informal learning. For example, we will scaffold student learning and hands-on experimentation in the following ways: (1) users will be provided with a set of problem exemplars that can be used as a guide to define their own problems and experiments; (2) rather than make the problem-solving task completely open-ended, we aim to work in course-lab environments, where lab instructors will supervise the use of the system or research supervisors will guide student projects; (3) we will develop a library of modules that illustrate issues of importance in CPS design and experimentation, *e.g.*, compatibility of interfaces, heterogeneity in modeling and analysis, synchronization of networked and distributed components across different time scales; and (4) provide facilities for students to communicate with their instructors and other students through the CPS-LaaS system as they work on their projects.

We envision several concrete realizations of the CPS-LaaS framework. For example CPS-LaaS system that uses robot blimps as the analogous system may be different from a system that uses discrete assembly stations as the analogous system. For each realization, we will identify exemplars that highlight the dominant cyber physical interactions in the system using the well-structured concepts of component-oriented compositional modeling paradigms we have developed for building large CPS models [11], [12]. Some of these exemplars will also highlight QoS and para-functional tradeoffs — for example in the case of CCS, the utilization of the virtual conveyor system will be tightly linked to the reliability, maintainability and rapid reconfigurability of the mobile units in the analogous system. Other exemplars will highlight safety issues (both in terms of equipment protection and to protect humans interacting with machines), robustness and reliability of networked control, and fault management while executing coordinated tasks [13], [14].

Problem-based learning for students will be enhanced by activities that use pre-defined model libraries to design, specify, operate, and monitor virtual CPS applications. Lessons from prior projects will be codified as demonstration projects and library modules. From a framing viewpoint, this approach combines problem- and example-based learning paradigms, while giving the students ample choice and leeway to work on projects that interest them. For example, consider the virtual conveyor systems that can be realized in CPS-LaaS using the analogous system shown in Figure 2. This analogous system admits rich possibilities for complex interactions that are described in [8].

The primary objective for the conveyor systems is to transport entities from some input port to an output port when each entity has its own target output port, deadline, and QoS constraints. In order to transport an entity that arrives on one horizontal track and leaves via a different one, the mobile robots moving on horizontal tracks must rendezvous with the robots that move along the vertical tracks. Thus, the spatio-temporal patterns of possible rendezvous limit the QoS that can be achieved in the virtual systems. Conversely, to achieve a desired QoS at the virtual layer, the transformation layer in CPS-LaaS must "design" the configuration of the analogous system such that rendezvous that are necessary to achieve the QoS can occur in the physical layer. Such problems are very interesting and challenging.

An important component of our education plans are to conduct a number of microgenetic studies, *i.e.*, observe students' use of the system and tools, where students need help from the instructors, and, where students need scaffolding to accomplish their model building, experimental setup, and experimental analysis tasks. We believe that once we have collected relevant data and information of student interactions with the system, not only can we use that information to improve system interfaces, but we can design scaffolds into the CPS-LaaS system as an independent module that students can query when they need help. If the student queries find a match, the system provides the feedback, otherwise, the query is passed on to an instructor or mentor, who can provide synchronous or asynchronous help, depending on their availability.

In addition to traditional learning outcomes, such as performance on the course exams and tests, participants in this validation exercise will be given conventional pre- and post-tests related to the problem domain, and asked to respond to a survey. The survey questions will ask for comparative experiences with the two versions — physical versus analogous that will provide us with valuable lessons on extending the scope of the systems, while ensuring the user experience and learning gains remain positive.

IV. CPS-LaaS for Massively Open Online Courses

Currently we are witnessing a new revolution in digital online learning called the Massively Open Online Courses (MOOCs) [15], [16]. MOOCs leverage the Internet and Web technology to offer online digital education to hundreds of thousands of users world wide. There are three fundamental limitations with current MOOC technologies if they must be used for CPS education: (1) how to develop a mechanism that allows manipulation of physical artifacts by the MOOC users; and (2) how to create many instances of the laboratory setups to accommodate hundreds of thousands of MOOC users, and (3) how to provide MOOC users with sufficiently challenging and meaningful problems, and develop formative assessment methods that support deep learning and developing problem solving capabilities [17]–[19].

The second issue is of paramount interest since unlike regular MOOC courseware, the same physical artifacts cannot be used by multiple users at the same time. Creating numerous laboratories to address this problem will be hugely expensive and complex. We believe that the scalable and networked architecture of CPS-LaaS will make it a realistic tool for offering laboratory-based CPS courses in the form of MOOCs on CPS topics. In fact, we believe that CPS-LaaS provides a much needed enabling technology for MOOCs to offer laboratory-based courses, which currently remains an unresolved problem for MOOCs [15]. Vanderbilt University is already a partner institution with MOOC providers, such as Coursera, and pilot offerings of courses by Vanderbilt faculty are currently being offered. Once our CPS-LaaS technology has matured, our goals are to develop one or more courses to be offered as a MOOC through collaborations with CPS researchers in other institutions.

V. Conclusions

In today's state of CPS education, not all students are in a position to obtain a balanced approach to CPS education involving both theory and practical hands-on training. Many limitations contribute to these deficiencies. To overcome this problem, this paper presented the concept of a CPS Laboratory-as-a-Service (CPS-LaaS), which offers a playground for CPS students to apply their theoretical knowledge and experiment with a variety of ideas. CPS-LaaS overcomes existing barriers to easy access to CPS laboratories by providing a virtualized CPS laboratory. These laboratories are not simulations but rather real physical testbeds to experiment with realistic behaviors. Moreover, CPS-LaaS is able to scale to the needs of a large number of students by using (collection of) analogous systems as the physical testbed that is virtualized for the users. CPS-LaaS is an enabling technology for massively open online courses to make laboratory-based courses feasible. Our current work is focusing on a concrete realization of CPS-LaaS in the context of a composable conveyor system.

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