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Board 60: WIP: A Comprehensive Design & Prototyping Platform for Rapid HW/SW Development Classes

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WIP: A Comprehensive Design & Prototyping Platform for Rapid HW/SW Development Classes

***Abstract*-**Robotics, autonomous transportation, and other computerized physical systems become widely accessible subjects for even a semester-long lecture and laboratory class. Sometimes, the physical systems are often transformed to cyber-physical systems (CPSs) by interfacing modules in physical systems to cyber system. It is often challenging for undergraduate students to implement a CPS comprising of analog and digital hardware and software within a limited period (e.g., ≈ 5 weeks) although they are accessible to highly automated development tools. In order to mitigate restrictions of a CPS development time and environment in a classroom, we have developed a *comprehensive design and prototyping platform (CDPro)* for rapidly designing and prototyping a miniature autonomous vehicle controlled via a cyber-control system as a CPS. The CDPro provides a real-time hardware-in-the-loop simulation with virtual and real prototypes. In particular, the CDPro is capable of performing high accuracy real-time simulations. Based on the CDPro development, a course has been offered for three academic years to introduce the concept of the CDPro and synthesize hands-on analog and digital systems and hardware and software integration experiments. The CDPro is expected to mitigate time-consuming learning and utilize the different modeling and prototyping tools from various vendors for class activities. The CDPro is also expected to be beneficial for students before and after their engineering education.

INTRODUCTION

Contemporary transportation and robots comprise various embedded hardware and software control and communication components in order to deal with critical features, such safety, autonomous capability, accuracy and complexity of control, and so forth. In general, the more embedded components are integrated in such cyber-physical systems (CPSs), the better overall performance of the CPS is feasible. Although electronic design automation (EDA) and platform-based approaches alleviate the amount of work and time for the prototyping and implementation of the systems in the industry, introducing a similar quality and quantity of prototyping and implementation of rapidly evolving CPSs is still one of the most time-consuming design activities in engineering education. Typically, there are a few combinations of design and prototyping approaches, including simulations/real-time simulations and virtual prototyping that are widely exercised in academia [1]. In particular, a real-time simulation, such as hardware-in-the-loop (HIL) simulation [2], with real-prototyping becomes one of the viable solutions for CPS hardware developers in the automotive industry. In addition, various complex subsystems in a CPS are seamlessly integrated into a real-time simulation environment while maintaining the intuitive and user-friendly operations, including precise design refinement and efficient evaluation. Furthermore, an automobile CPS is one of the most viable applications for benefiting from Internet-of-things (IoTs), which gather various forms of information from numerous types of sensors via wireless communication and process the information on embedded or application-specific processing engines [3]. In lieu of the real-time simulators for the specific applications that performed well, the baseline simulation environment must maintain the important features addressed before. Therefore, more perceptive HIL simulations are recommended. Unlike in the industry, simple and limited scope of real-time applications related in CPSs have been dealt with in real-time simulations in academia. Although usage of real-time simulators in the classroom grows [4], academic versions of real-time simulators [5] include limited features of real-time simulations to handle laboratory exercises inter-operable with equipment. Particularly, some other features, including user-friendly interfaces, the intuitive expansion, and multiple user support, are often more important than realistic and large scale prototyping, which increases the gap between the industrial and academic practices [6].

We introduce a comprehensive modeling and prototyping platform (CDPro) for rapidly designing and prototyping CPSs, including a simplified autonomous vehicle controlled via a CPS. More specifically, the CDPro has been developed to enhance the seamless integration and intuitive interface of various virtual and real hardware and models used for research and education in academia. The CDPro provides an FPGA-based virtual prototyping extensible to HIL real-time simulation with real prototypes. The CDPro has been utilized for applications discovered in the inter-disciplinary research and education in CPS, Computing, and Communications. Particularly, the CDPro performs automotive electronics research including an automated collision prevention system installed on an autonomous electric vehicle (AEV) prototype.

Section 2 introduces the platform architecture and key operations of the CDPro. Section 3 describes a CDPro evaluation with models for real-time simulations integrated to virtual prototypes and a real prototype via wireless interface modules for a rapid CPS design and prototyping. The evaluation results and analysis of the CDPro with the CPS prototype are depicted in Section 3. Section 4 elicits the conclusions and future works.

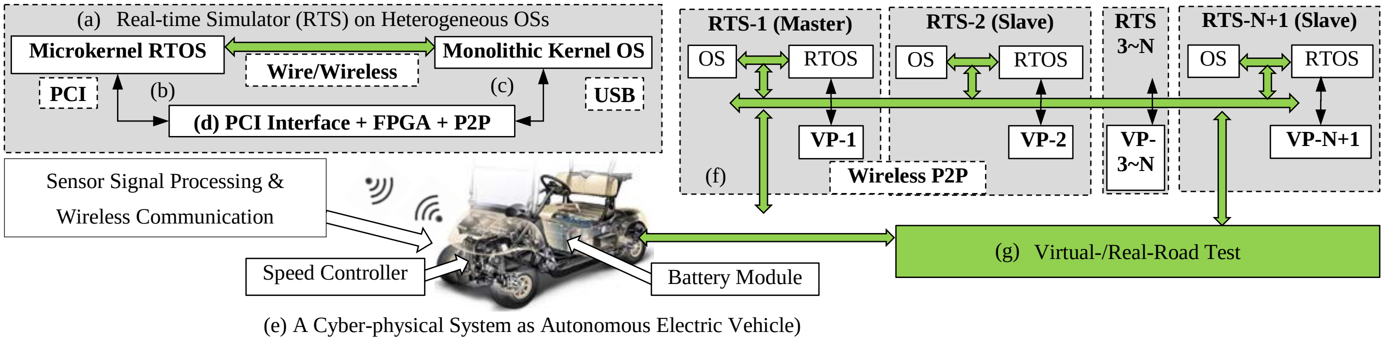

Figure 1. A block diagram of the CDPro platform for prototyping an autonomous electric vehicle interfaced to a FPGA-based virtual prototyping and a hardware-in-the-loop real-time simulations via extensible wireless communications; PCI: peripheral component interconnect; P2P: peer-to-peer wireless

Design of the Comprehensive Modeling and Prototyping Platform (CDPro)

A block diagram of the CDPro architecture is illustrated in Figure 1. In Figure 1, a real-time simulator consists of (a) heterogeneous operating systems (i.e., microkernel real-time OS) and monolithic kernel OS) connected via (b) a 100 Mbps Ethernet (i.e., IEEE 802.3u), (c) an 11 Mbps WiFi (i.e., IEEE 802.11b), and (d) a field-programmable gate array (FPGA)-based virtual prototyping system interface to the real-time simulator via a peripheral component interconnect (PCI) and multiple peer-to-peer (P2P) wireless devices. An autonomous electric vehicle prototype, shown in Figure 1 (e), comprises of sensor modules, a sensor signal processing and wireless communication module, a speed controller, a battery module, and others. Figure 1 (f) illustrates an extended real-time simulation capacity with multiple real-time simulations (RTSs) and virtual prototyping (VPs) systems for performing a remote virtual-and real-read test in the future.

A. *Real-time Simulations with Virtual Prototypes in the CDPro*

In the CDPro, software models, virtual hardware models, and real components in a real prototype (e.g., a miniature autonomous car for classroom activity) are concurrently running on a unified real-time HIL simulation environment. Software and hardware models are developed through a computer running on a monolithic kernel OS. A built-in modeling procedure is integrated with modeling tool suites, such as Matlab/Simulink for software models and Xilinx with hardware description language (HDL) for hardware models. After configuring and compiling virtual prototyping models, the software models for operating HIL real-time simulations is deployed to the real-time simulator. The real-time simulator partitions and schedules the software models and the virtual prototypes before allocating the executable software and hardware models to the available cores. Custom Simulink system functions, S-Functions, are developed for seamless integration between virtual prototypes and intuitive user interface. The generated S-Functions are configured to generate the inline macro call required to access the shared memory region where inputs to and outputs from the models allocated are available for exchanges.

Thereby, the virtual models and the real prototype can exchange their inputs and outputs via the shared memory region partitioned under the real-time simulation environment. Similarly, the AEV prototype, including sub-modules installed on the AEV, must be integrated to the real-time simulator by creating and configuring the associated interface models for the HIL real-time simulation.

B. *Real-time Simulations with Virtual Prototypes and a Cyber-physical System as a Real Prototype in the CDPro*

Up to three concurrently operating, different types of modules (i.e., software models, hardware models as virtual prototypes, and components in a real-prototype) in the CDPro can perform a HIL real-time simulation. The software models execute together via the allocated regions in the shared memory. The virtual prototypes running on the FPGA are interfaced to the associated software models via the different regions in the shared memory through the PCI. As seen in Figure 1, the CPS, an AEV, also co-operates with the associated software models and virtual prototypes via the wireless communication channel established with the IEEE 802.15.4 due to mobility of the CPS. Since CPSs generally require both analog and digital signal interfaces, the interface module must be capable of operating analog-to-digital and digital-to-analog (ADC/DAC) conversions. Finally, the CDPro launches threads to service three different types of executables via established wire and wireless interfaces. During the HIL real-time simulations in the CDPro, the threads scheduled according to the partitioning scenarios and priority are running in parallel. The HIL real-time simulation results are collected as "μ second" and stored to temporary files. The client-server socket-based Ethernet (IEEE 802.3.u) or WiFi is also available for multi-stations and multi-CPSs developments.

A Rapid Cyber-physical System Design Course Development with CDPro

A rapid CPS design course with the CDPro was developed. This 3-credit hour course primarily aims to offer students to learn hardware/software modeling techniques and prototyping experiences on real-time CPSs within a single semester. Main course objectives include teaching the concepts of the integrated software modeling and hardware virtual prototyping techniques. The key subjects taught in the course include (1) CPS modeling based on Matlab/Simulink, (2) FPGA-based virtual prototyping in VHDL, and (3) an integration of the CPS real-prototype. Other key lab activities installed in the course are to (1) design with Labview and C#-based GUI, which facilitates prompt and accurate model and prototype integrations; (2) develop a miniature CPS, such as an autonomous electric vehicle real-prototype that serves as a reduced-scale realistic design and verification opportunity to explore important aspects of real-time CPS development; (3) design time sensitive software and hardware components for real-time applications; (4) interface components in three different forms (i.e., software model, hardware virtual prototype, and real-system prototype) in multi-level design and test abstracts with wire and wireless communication channels; and (5) explore consolidated real-time HIL simulations. The course, in conjunction with laboratory exercises, is to improve rapid design and implementation opportunities and hands-on experiments for an individual and a group. In the near-future, more comprehensive test capability will be added to the CDPro. For example, the CDPro would be able to remotely access multiple autonomous vehicles operating simultaneously on an external testing track mounted. Table I shows a summary of the course objectives identified and key subjects to teach in detail.

TABLE I. A COURSE SUMMARY AND KEY SUBJECTS OF THE RAPID CYBER-PHYSICAL SYSTEM DESIGN WITH CDPRO

Course Objectives	Key Course Subjects
Understand real-time simulator design concept and flow	Interface between heterogeneous operating systems; GUI-based or high-level language programming
Develop skills for FPGA-based hardware virtual prototyping	Hardware description language (HDL)-based virtual prototyping
Programming language-based software modeling	Mixed assembly and high-level programming in embedded software
Integrate software models and virtual-/real-prototypes for HIL real-time simulations	Microcontroller-based real prototyping Interface between (1) software and software, such as programming with different languages; (2) virtual and real prototypes, such as FPGA and microcontroller; and (3) embedded software and hardware with microcontroller boards
Perform data processing and signal acquisition in real-time	Labview-based analog and digital signal acquisition

Table II summarizes design and development tool suites used in the course. There are three main software and hardware design and prototyping types—(1) software modeling, (2) virtual hardware modeling and prototyping, and (3) real hardware and software prototyping—that are employed to perform different types of real-time simulations in the CDPro. As shown in Table II, the most commonly used programming languages are (1) Matlab, (2) C/C++, or (3) JAVA. The GUI-based intuitive programming is done with Simulink, Labview, and C# programming. Xilinx & Altera's FPGA-based design suites are popular for virtual prototyping with HDL. Real prototyping frequently employs various microcontroller boards and the associated development tools, including Arduino microcontroller IDE, Microchip's PIC series and MPLAB, and ARM's Keil MDK development studio. Other real hardware prototyping, including sensors and wireless communication devices for IoT applications, can be exercised under the CDPro.

As depicted, this course requires the use of various programming languages and tool suits, FPGA-based virtual prototyping with VHDL, and real-system prototyping with microcontrollers, sensor modules, and wire/wireless interfaces. Therefore, this course was initially offered to the first-year Master students without any prerequisite. However, an almost similar course was offered to senior undergraduate students with a series of prerequisites, including Rapid Prototyping with FPGA, Advanced Digital Design with HDL, Embedded Systems Design, Embedded Kernel & RTOS, and others. As seen Table II, there are various design tools used in the course. Although most of the tools are used in other courses, students are often reminded whenever different tools are used.

TABLE II. A SUMMARY OF DESIGN AND DEVEELOPMENT TOOL SUITES EMPLOYED IN THE COURSE

Type of Real-time Simulations	Design Types	Design & Verification Tools
SIL	Software Modeling	Programming languages, Matlab, C/C++, or JAVA; Visual Studio
SIL	Software Modeling & GUI-based Programming	Simulink; Labview; C# Visual Studio
HIL/VIL	Hardware Modeling & Prototyping	FPGA; VHDL/Verilog Programming; Xilinx; Quartus Prime
HIL/VIL/RIL	Real Prototyping with microcontroller boards for CPSs	ARM Keil MDK; PIC32-MPLab; Arduino

Type of Real-time Simulations: SIL (Software-in-the-loop), HIL (Hardware-in-the-loop), VIL (Virtual-prototype-in-the-loop), RIL (Real-prototype-in-the-loop)

THE COURSE ASSESSMENT

The CDPro-based comprehensive design methodology and the real-time simulation platform have been deployed for classroom exercises during the past few semesters. Three different modeling and prototyping with commercial design tool suites were also used for performing adequate types of real-time simulations with the CDPro platform. Model interface between software/hardware and virtual-/real-prototype are experienced throughout the CDPro platform. In particular, different types of HIL simulations are explored by students with various levels of hardware/software co-design and verification tasks, including performing comprehensive software modeling and virtual-/real-prototyping in the course.

TABLE III. STUDENT OUTCOMES ASSESSMENT FOR TWO YEARS

Student Outcomes	Correlated Course Outcomes	EAMU Average	
		Year 2	*Year 1*
Evaluate and utilize research methodologies appropriate to the discipline	Understand real-time simulator design concept and flow	3.95	4.11
Master the skills, methods, and knowledge appropriate to the discipline	Develop skills for FPGA-based real-time HW/SW modeling and integration	4.30	3.56
Access, analyze, and evaluate information	Develop proficiency with contemporary tools	5.00	4.22

EAMU: E (Excellent), A (Adequate), M (Minimal), U (Unsatisfactory)

A few key assignments were identified for measuring the performance of students. Three course outcomes defined were justified. The measured student performance was assessed through the assessment strategies implemented on an online assessment tool.

1) Course Outline

The CDPro presented is for designing and testing various CPSs in a comprehensive real-time simulation with a hardware prototyping environment. Laboratory exercises offer to learn hands-on experiences and practical design and test knowledge in various levels of abstracts. In particular, the course was focused on offering a series of system-level design experiences to a group of students while increasing the complexity and scale of the target systems. Therefore, each student group confidently delivered the expected outcomes of the given lab exercises. In addition, individual students achieved proficiency with contemporary design and analysis tools. Each team member was capable of demonstrating the ability to deliver expected solutions via more than one way to satisfy the design requirements within the limited time.

The key assignment for understanding the different types of real-time simulations with CDPro shown in Table II provides an opportunity to explore and understand the capability of different SIL/HIL simulations according to the characteristics of the target CPSs. Another key assignment is to analyze and optimize an implementation experiment of the FPGA-based virtual prototyping integrated with a real CPS. We eventually assessed the student outcome– "to master the skills, methods, and knowledge appropriate to the discipline." A comprehensive final project is aimed to evaluate proficiency of hardware and software design and analysis with contemporary tools integrated in the CDPro platform.

2) Inter-assesment of the Course

Internal assessments are identified according to the three primary frameworks classified in the course outline. The assessment evidences are collected from the key assignments given: (1) review and presentation of research manuscripts, (2) laboratory experiments through SIL/HIL simulations with the CDPro platform, and (3) real prototyping of a CPS with the CDPro platform, for the specific periods. The key assignment outcomes and the corresponding ABET student learning outcomes are assessed by the construction of the heuristic rule-based EAMU performance vector in four categories, which consists of Excellent (≥ 90%), Adequate (≥ 75%), Minimal (≥ 60%), and Unsatisfactory (< 60%).

As seen in Table III, the assessment results of the course were obtained from a total of 34 students enrolled in two consecutive years. According to the EAMU scores from the student groups, which were 3.95 & 4.11, the groups of students were encouraged to learn more knowledge on different types of real-time simulations and related applications. The 20.79% EAMU score increase of the second student group indicated that the student group became familiar with modeling and integration activities with the CDPro platform. Consequently, assessment results of all five students groups showed the highest EAMU score, 5.0, from their final projects.

3) Intra-assesment of the Course

After analyzing the intra-assessment results, the overall course outcomes and ABET student learning outcomes were evaluated with the faculty course assessment report (FCAR) [7]. FCAR has two components–formative and summative components. The performance of students was monitored under the formative component, which allows the instructor to identify and satisfy the student's needs. On the other hand, the summative component determines the attainment of the course outcomes and ABET student learning outcomes measured from the EAMU performance vector. As a result, FCAR is useful for the self-assessment of the course outcomes.

CONCLUSIONS

We developed the CDPro real-time simulation platform for designing and implementing various subsystems of CPSs in rapid and intuitive system integration and for facilitating interface of multi-levels of abstracts in traditional CPS design and the verification processes. The CDPro platform allows inexperienced individuals and groups of students to accelerate their design and implementation learning experience in an intuitive and systematic manner. In particular, the CDPro platform enables to interface heterogeneous systems and various types of real-time verifications. The CDPro platform offers the important real-time simulation capabilities, including (1) operation accuracy (i.e., less than 2.89% of sensor system test), (2) fast HIL real-time simulation (i.e., 2.5 times faster acceleration of a speed controller than Simulink acceleration), (3) accurate HIL real-time simulation (i.e., 0.3% HIL simulation difference compared to Simulink simulation), (4) precise real-time resolution of HIL real-time simulation (i.e., 50 μsec responding timing constraints), and (5) user friendly model integration and heterogeneous prototype interface over different abstract levels.

The course comprises of a series of lectures related to the subjects for successful designing and utilizing the CDPro platform and related applications in Computer, Communication, Electrical, and Power-Electronics Engineering. Hands-on laboratories equipped with hardware/software design tools were also integrated for further experiments of emerging CPS applications. The course is expected to alleviate the technology gap developed and utilized between the industry and academia. It will also be beneficial for students to prepare for their professional careers in the rapidly evolving technological environment.

FUTURE WORKS

The CDPro consists of multiple real-time simulators, and is proposed for rapid prototyping of CPSs (i.e., autonomous electric vehicles). The real-time simulator comprises of heterogeneous OSs (i.e., microkernel RTOS/monolithic-kernel OS) running on multicore machines interfaced via wire/wireless network and PCIs configured as a master-slave network topology. Therefore, the CDPro provides an intuitive and swift integration of the components/subsystems developed in different stages and performs the hardware-in-the-loop simulations with software models/virtual-/real-prototypes over various stages of the design, verification, and upgrade. The CDPro dynamically rescales and relaunches various scales and complexities of target models/prototypes/testbenches while satisfying required real-time constraints.

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BIOGRAPHICAL INFORMATION