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Cyber-Physical-Human Systems Course (CPHS)

Course ID:		Elective Course
Name of the Course: **Cyber-Physical-Human Systems**		
Credit Unit	Number of hour / Week	Number of Week / Semester
In class lecture: 3	In class lecture: 3	18 (incl. Exams)
In laboratory project: 1	In laboratory project: 3	18 (incl. Exams)

Course Description

Cyber-physical Systems (CPS) are emerging from the integration of embedded computing devices, smart objects, people and physical environments, which are typically tied by a communication infrastructure. Applications of CPS include new generation automotive systems, high confidence medical devices, avionics, smart power infrastructure, process control, distributed robotics, and others. These also include systems such as Smart Cities, Smart Grids, Smart Factories, Smart Buildings, Smart Homes and Smart Cars.. All such systems exhibit stringent real-time and safety requirements: computation must progress in parallel with physical processes in the environment, and system disruption can lead to catastrophic consequences.

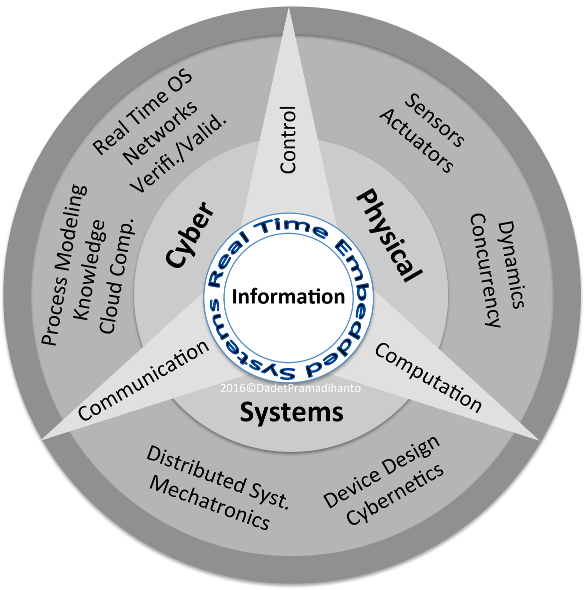

Figure 1. Cyber-Physical-Systems

This course covers concepts, theory and research issues in safety-critical embedded systems and Cyber-Physical Systems (CPS), with a focus on the architectural design and analysis of the underlying hardware/software computing system. Topics include: challenges in CPS design, predictable computer architectures, scheduling of hardware resources, operating system abstractions for CPS, timing and performance analysis, modeling and verification, CPS applications.

Course Objective

The goal of this course is to introduce the students to the key challenges, design methodologies and research directions in the field of cyber-physical systems, with an emphasis on the design of the underlying computing architecture. In particular, we will show how CPS requirements of predictability and reliability lead to significant changes in the hardware architecture, and we will study state-of-the-art solutions in this area. Due to the multidisciplinary nature of CPS design, the course will also touch on related topics, including: predictable operating system abstractions, timing analysis, modeling and verification.

- Introduce the challenges in CPS design and how they correlate to the areas of computer architecture and system programming.
- Provide a multidisciplinary overview of key topics in CPS design.
- Appreciate the CPS requirements of timeliness, composability and predictability and be able to apply them to the design of computing architectures.
- Teach essential skills to perform research and development in the CPS field.

Textbook

1. Edward A. Lee and Sanjit A. Seshia, *Introduction to Embedded Systems, A Cyber-Physical Systems Approach*, Second Edition, http://LeeSeshia.org, ISBN 978-1-312-42740-2, 2015.
2. Karl J. Aström and Richard M. Murray, *Feedback Systems, An Introduction for Scientists and Engineers*, Second Edition, Princeton University Press, ISBN-13: 978-0-691-13576-2, 2012.
3. Giorgio Buttazzo, *Hard Real-Time Computing Systems, Predictable Scheduling Algorithms and Applications*, Springer, ISBN 978-1-4614-0676-1, 2011.

Prerequisites

Undergraduate-level knowledge of computer architecture, operating systems, embedded systems, digital control systems and computer networking is welcomed but not required.

Course Outline

The following topics will be covered in class and in laboratory; the number of hours per topic and the detailed content is approximate and shown in table 1..

- **Introduction to CPS.** CPS as the next evolution of embedded systems. Key issues in CPS design: timing predictability, verification and certifiability, integration and composability, modeling and abstraction, commercial of the shelf (COTS) components and time-to-market. Overview of topics covered in the course. Research opportunities in CPS. Introduction to course project.
- **Modeling of Dynamics Systems: Continuous and Discrete Time**. Overview of Mathematics foundation for modeling dynamics systems. Some example on modeling of continuous system (mechanical, electrical, etc.) and discrete-event systems.
- **Introduction to Real-Time Systems.** Task model. Quality of service. Interplay between timing properties and digital control. Basic

schedulability results. The worst-case execution problem. The end-to-end delay problem.

- **Applications of Cyber-Physical Systems.** Overview of CPS applications. IMA (Integrated Modular Avionics) design. Issues in ARINC 653. AUTOSAR (AUTomotive Open System ARchitecture). Further examples of medical systems, power grid control, monitoring applications.
- **Predictable Computer Architectures.** Impact of architectural features on predictability. Controllable pipelines. Cache partitioning strategies. Scratchpad memories. Bus scheduling. Network-on-chips and real-time. Predictable memory controllers. Heterogeneous systems (FPGA, GPGPU).
- **Predictable OS Abstractions.** Overview of Real-Time OS and Hypervisors. Interrupt scheduling. Hierarchical and component-based OS. Predicable task execution. Parallel execution models.
- **Timing and Performance Analysis.** Overview of static analysis methodologies. Measurement-based techniques. Cache, bus and memory analyses. Real-time queuing theory. Network calculus. Real-time calculus.
- **Introduction to Models of Computation and Verification for CPS.** Hybrid models. Timing verification. Hardware run-time monitoring. Tools and architectural description languages.
- **Human-in-the-loop Cyber-Physical-Systems**. Efficient embedded system design. Cognitive intent detection algorithms using brain or other neurophysiological signals. Actuator and robotics to realize an intended outcome or effect in the physical world. Distributed sensor architectures with suitable, power-efficient communication mechanisms.

Laboratory Projects

The following topics will be covered in laboratory; the number of hours per topic and the detailed content is approximate and shown in table 1

- **Networked Control of Dynamical System** (6 DoF Ball Balancing Problems). Systems modeling, control design, embedded system implementation, sensing (IMU and capacitive/resistive planar sensor, etc.), implementation of direct control and control over networks, and performance analysis
- **Remotely Operated Vehicle to Locate Water Monitoring Sensors**. System modeling, control design, sensing using IMU, embedded systems implementation, wired and wireless human-in-the-loop operation of ROV, sensing of water parameters, and sensing data communication to server.
- **Mixed Criticality Scheduling and RTOS**. Based on the two examples of CPS above, we analyze the different criticality on the systems (mixed criticality). How we evaluate the scheduling algorithm, which involve the mixed criticality, and how we implement it on the RTOS to guarantee the mixed deadline.
- **Performance Analysis, Computation Model and Verification of CPS**. Evaluation of the above CPS's, and perform timing verification and hardware run time monitoring.

The Course Assessment Matrix and Weekly Course Schedule of the CPS are shown in **Table 1** and **Table 2**. In Table 1 shows the learning objective in relation with learning outcome criteria (see Table 2).

Table 1. Course Assessment Matrix and Weekly Course Schedule (see Table 2.)

Week	Learning Objectives	Outcome Criteria						
		a	b	c	d	e	f	g
	In Class Activities (3 hour / Week)							
1	**Introduction to CPS**: CPS as the next evolution of embedded systems. Key issues in CPS design: timing predictability, verification and certifiability, integration and composability, modeling and abstraction, COTS components and time-to-market. Overview of topics covered in the course. Research opportunities in CPS. Introduction to course project			2	2			1
2	**Modeling of Dynamics Systems: Continuous and Discrete Time**. Overview of Mathematics foundation for modeling dynamics systems. Some example on modeling of continuous system (mechanical, electrical, etc.) and discrete-event systems	3						
3 - 4	**Introduction to Real Time Systems**. Task model. Quality of service. Interplay between timing properties and digital control. Basic schedulability results. The worst-case execution problem. The end-to-end delay problem	3		2				
5	**Application of Cyber-Physical Systems.** Overview of CPS applications. IMA (Integrated Modular Avionics) design. Issues in ARINC 653. AUTOSAR (AUTomotive Open System ARchitecture). Further examples of medical systems, power grid control, monitoring applications	3		3	3			1
6 - 7	**Predictable Computer Architecture**. Impact of architectural features on predictability. Controllable pipelines. Cache partitioning strategies. Scratchpad memories. Bus scheduling. Network-on-chips and real-time. Predictable memory controllers. Heterogeneous systems (FPGA, GPGPU)	3		2				1
9	**Midterm Exam**							
10-11	**Predictable OS Abstraction.** Overview of Real-Time OS and Hypervisors. Interrupt scheduling. Hierarchical and component-based OS. Predicable task execution. Parallel execution models	3		2				1
12-13	**Timing and Performance Analysis**.Overview of static analysis methodologies. Measurement-based techniques. Cache, bus and memory analyses. Real-time queuing theory. Network calculus. Real-time calculus	3		2				
14-15	**Introducation of Model of Computation and Verification for CPS.** Hybrid models. Timing verification. Hardware run-time monitoring. Tools and architectural description languages	3		2				
16	**Human-In-The-Loop Cyber-Physical-Systems**. Efficient embedded system design. Cognitive intent detection algorithms using brain or other neurophysiological signals. Actuator and robotics to realize an intended outcome or effect in the physical world. Distributed sensor architectures with suitable, power-efficient communication mechanisms	3		2				
8 & 17	**Student Presentation.** Student reading, present and discuss two journal paper on CPS	3				3		2
18	**Final Exam**							
	In Laboratory Activities (3 hours / Week)							
1 - 4	**Project 1**: Networked Control of Dynamical System (6 DoF Ball Balancing Problems)	3	3	2	1	2	2	3
5 - 8	**Project 2**: Remotely Operated Vehicle to Locate Water Monitoring Sensors	3	3	2	3	2	2	3
10 - 13	**Project 3**: Mixed Criticality Scheduling and RTOS	3	3	2	1	2	2	3
14 - 17	**Project 4**: Performance Analysis, Computation Model and Verification of CPS	3	3	2	3	2	2	3

Table 2. Outcome Criteria

Outcome	Criteria
a	Ability to apply mathematical, science, and engineering principles to the identification, formulation, and solution of engineering problems
b	Ability to design and conduct experiment and to analyze and interpret data using modern engineering tools and techniques
c	Ability to design a system, component, or processes and products to meet desired needs
d	Ability to analyze important social and environmental problems and identify and discuss ways that engineers might contribute to solutions, including technological, economic, and ethical considerations in the analysis.
e	Ability to communicate effectively in both writing and speaking in a variety of professional contexts
f	Ability to function effectively in both single-discipline and multidicipline teams
g	Recognition of need for and ability to engage in lifelong learning
Note: **1** = Objective adresses outcome slightly, **2** = moderatly, **3** = subtantively	

Instruction and Assesment

Figure 2 shows the element of course design (Felder & Brent, 2003). In general a course composed of learning objective, instruction techniques, and assessment measures that should be perform and achieve by student and lecturer.

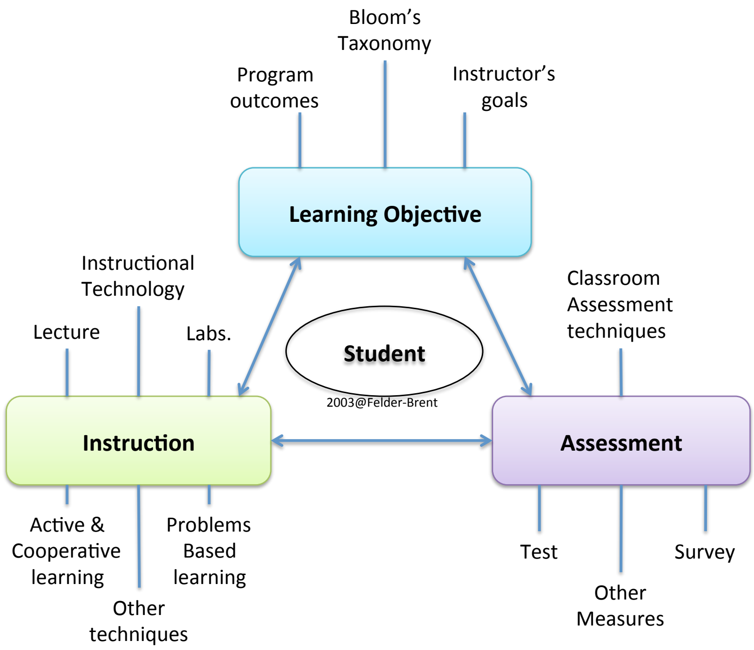

Figure 2. Element of course design (Felder & Brent, 2003)

The learning objectives of Cyber-Physical-System course have been discussed previously. To achieve the learning objective, in this course we used the instruction techniques that adopt the combination of active & cooperative learning and problems based learning for both in class lecture and in laboratory projects.

The assessment processes will be conducted intensively in class and in laboratory by evaluating the performance of student weekly. Beside that, as already mention in Table 1, the assessments are also perform by midterm and final examination.

References

1. Edward A. Lee and Sanjit A. Seshia, *Introduction to Embedded Systems, A Cyber-Physical Systems Approach*, Second Edition, http://LeeSeshia.org, ISBN 978-1-312-42740-2, 2015.
2. Karl J. Aström and Richard M. Murray, *Feedback Systems, An Introduction for Scientists and Engineers*, Second Edition, Princeton University Press, ISBN-13: 978-0-691-13576-2, 2012.
3. Giorgio Buttazzo, *Hard Real-Time Computing Systems, Predictable Scheduling Algorithms and Applications*, Springer, ISBN 978-1-4614-0676-1, 2011.
4. Richard M. Felder and Rebecca Brent, *Designing and Teaching Courses to Satisfy the ABET Engineering Criteria*, Journal of Engineering Education, pp. 7-25, 2003.
5. Giancarlo Fortino, Giuseppe Di Fatta, Sergio F. Ocha (ed.), *Special Issue on "Cyber-Physical Systems (CPS), Internet of Things (IoT) and Big Data*, Journal on Future Generation of Computer Systems, Elsevier, to appear in October 2016.