Experiences with A First Course on Cyber-Physical Systems * †

Walid Taha
Halmstad University
and Rice University

Robert Cartwright
Rice University
and Halmstad University

Roland Philippsen
Halmstad University

Yingfu Zeng
Rice University

Abstract

Effective and creative cyber-physical systems (CPS) development requires expertise in disparate fields that have traditionally been taught in several distinct disciplines. At the same time, students seeking a CPS education generally come from diverse educational backgrounds. In this paper, we report on our recent experience developing and teaching a course on CPS. The course addresses the following three questions: What are the core elements of CPS? How should these core concepts be integrated in the CPS design process? What types of modeling tools can assist in the design of cyber-physical systems? Our experience with the first two offerings of the course has been positive overall. We also discuss the lessons we learned from some issues that were not handled well. All material including lecture notes and software used for the course are openly available online.

1. Introduction

CPS innovation requires mastery of concepts and skills that are traditionally assigned to distinct disciplines. At the same time, students seeking a CPS education come from diverse educational backgrounds with differing expertise. This situation makes it diffiult to explain to students why CPS design is technically challenging and to identify what tools and methods can empower CPS developers to overcome the technical problems involved in creating new systems.

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This paper describes a first course designed to address these challenges. The course focuses on answering three questions:

- What are the core elements of CPS?
- How should these core concepts be integrated in the CPS design process?
- What kinds of modeling methods and tools can help students create innovative cyber-physical systems?

Since this course was developed in Sweden at Halmstad University, compliance with the Bologna Process [3] mandated developing a formal syllabus [1] including a precise statement of examinable educational outcomes. The Bologna Process is a series of agreements between European countries aimed at ensuring that the educational systems in various countries are comparable.

All materials developed for our course are freely available under appropriate open licenses. The living (continually evolving) lecture notes are available online [6] under a Creative Commons license (Figure 1). A portable (JVM-based) distribution of the interactive modeling and simulation environment used in the course is also available online [2] under a GPL license (Figure 2).

2. Educational Outcomes

The published formal syllabus [1] for the course identifies the expected educational outcomes. Unfortunately, this formal description relies on the specialized vocabulary and terminology used to describe other components of the masters programs in Embedded and Intelligent Systems (EIS) at Halmstad University. From the perspective of the broader CPS community, the course can more effectively be described as helping students to:

- Recognize the scope and scale of the potential impact of CPS innovation;
- Understand why many of tomorrow's innovations will be in CPS;
- Develop lifelong, sustainable skills and sensibilities for the analysis and design of innovative cyber-physical systems, including
  - back-of-the-envelope estimation;
  - familiarity with the fundamental sources of complexity in CPS design (such as system size, nature of continuous dynamics, discrete state size, different types of

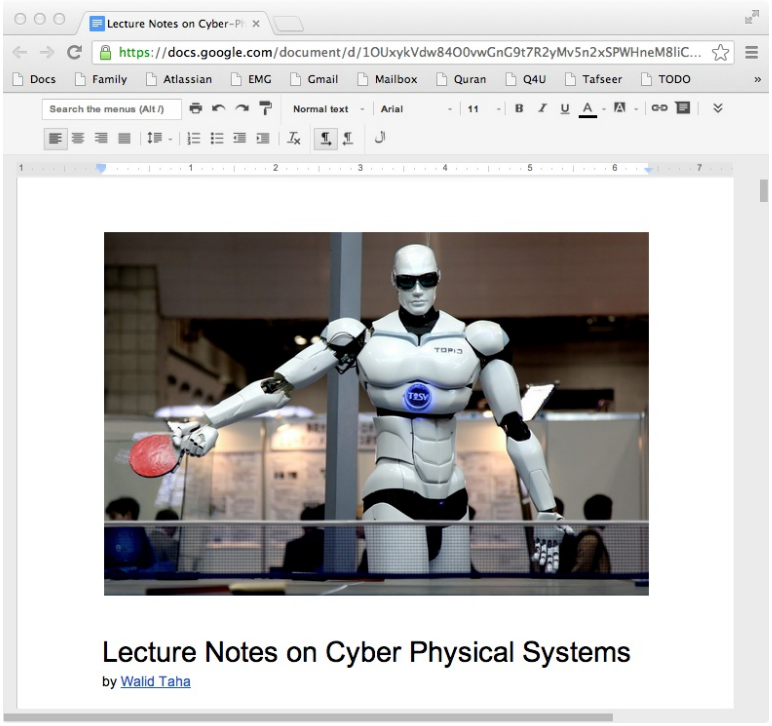

Figure 1: The Course Notes are freely available online under a Creative Commons license.

  uncertainty); and
  - facility with virtual experimentation;
- Gain experience with the mathematical modeling and simulation of hybrid systems and the issues that arise when building and validating such models;
- Assimilate a conceptual model of the CPS development process, and master the terminology and communication skills required to analyze and critique development processes; and
- Develop an awareness of the scientific, engineering, and social aspects of CPS.

Our CPS course seeks to realize these educational objectives by concentrating on the topics described in the following section.

3. Core Elements and Topics of CPS

The course follows lecture notes [6] consisting of eight chapters. The material is covered at a rate of two lecture hours and two lab hours per chapter during an eight-week term. Each chapter focuses on a topic that we view as a core element of CPS:

1. The critical importance of research and education in CPS ("What is a CPS?");
2. Modeling Physical Systems;
3. Hybrid Systems;
4. Control;
5. Modeling Computational Systems;
6. Communications;
7. Representative Case Study: A Single-Link Robot;
8. Agent-based Systems and Games.

The sequencing of these chapters is determined primarily by dependence. With one exception, each chapter draws on and explicitly reinforces the preceding chapters. The exception is the last chapter, which does not depend on the preceding case study. The case study immerses students in a particular class of physical systems and helps them successfully complete the course project, a major milestone in the class.

To accommodate students from diverse backgrounds, each chapter contains a largely self-contained introduction to the designated topic. To reinforce the connections between topics, several examples and themes are shared across chapters. Notably, the concept of prototype equations (first and second order differential equations) is introduced in the first chapter and revisited in almost every chapter as a mathematical characterization of different concepts and phenomena that arise in CPS. In this way, differential equations are introduced in the first week of the course and students practice using them throughout the term. Similarly, issues relating to energy and delay are introduced and revisited in different chapters during the course. Naturally, composing a coherent set of lecture notes for such a diverse set of topics requires the construction of a common framework of terminology and concepts, which helps accentuate the differences in focus among the various disciplines involved in CPS.

The development of these lecture notes has been influenced by ongoing interdisciplinary collaborations with colleagues at various institutions and corporations. Most of the material in the introduction is based on joint work and discussions with colleagues from industry (Schlumberger, AB Volvo) and on discussions with numerous researchers from the US National Science Foundation (NSF) CPS commu-

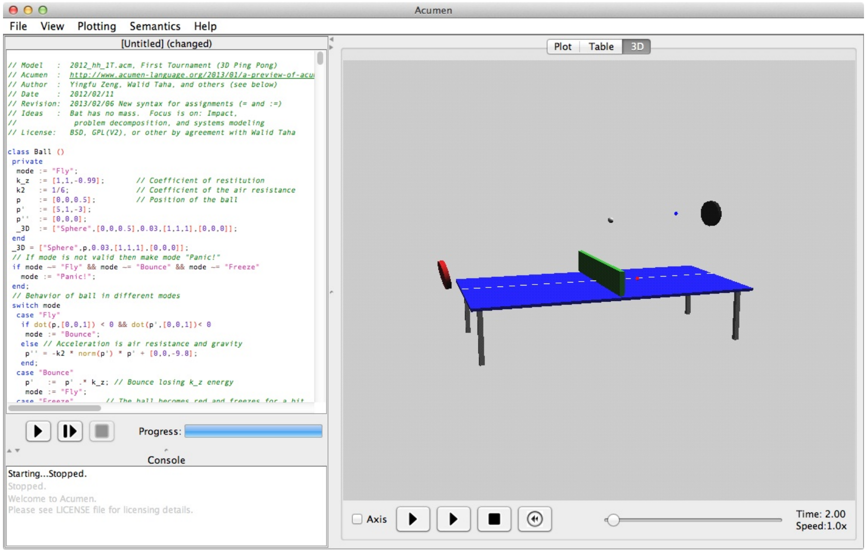

Figure 2: Acumen, a free open source hybrid-systems modeling and simulation environment used to teach CPS.

nity. The chapters on Modeling Physical Systems, Hybrid Systems, and Control have been strongly influenced by collaborations with two professors of Mechanical Engineering, Marcia O'Malley from Rice University and Aaron Ames from Texas A&M University, in the context of an ongoing NSF CPS project on Robot Design. They played a direct role in shaping our understanding of classical mechanics, variational principles, Lagrangian modeling, and the use of hybrid systems in modeling physical systems. Designating agent-based systems and games as a core topic of CPS was motivated by their utilitiy in addressing notions of cooperative and competetive behavior. Their inclusion was inspired by the work of Tony Larsson, a professor of real-time and embedded systems at Halmstad University, and of several other professors at the CERES and CAISR research centres at Halmstad University.

4. Teaching Materials

The course materials consist of lecture notes, a modeling and simulation environment, a project, and external resources. In this section we describe these materials in more detail.

4.1 Open Lecture Notes

As noted above, the lecture notes are divided into eight chapters. We are in the process of expanding each chapter from an outline to an expository narrative consisting of approximately fifteen pages of typeset text; most of the eight chapters have already been expanded. We expect to continue to expand and revise the lecture notes as long as we teach the course.

4.2 Modeling & Simulation Environment

The modeling and simulation environment used in the course is Acumen [2, 7], an interactive environment for modeling distributed dynamic hybrid systems. Acumen is used in the course project, laboratory sessions, and some of the homework assignments. It is a development environment and interpreter for a small textual language. The textual language consists of constructs that correspond to concepts from either continuous or discrete mathematics. Our design premise is that building a tool around a parsimonious textual core has several important benefits. First, it provides a bound on the intrinsic complexity of the concepts that the students must master during the course. This bound helps ensure that students from diverse backgrounds have a fair chance of learning and mastering the environment quickly. Second, once students learn the core formalism from some canonical examples, this formalism serves as a common framework for articulating the concepts being taught. An environment that is easy to master helps empower students to become nascent CPS developers and encourage them to experiment with putative designs. In essence, Acumen is designed to inspire students to become CPS hackers. A tool that makes it easy to construct 3D animations of CPS code (Figure 5) transforms modeling and simulation into a creative game, making it much more intuitive. Rigorous design is what we ultimately want students to *do*. To achieve that goal, we must provide them with an engaging and entertaining environment for CPS design. By using such an environment to solve a carefully orchestrated sequence of exercises, students can gradually become adept at virtual experimentation and CPS design. Our theory is that "hacking" and "playing" turn learning about mathematics, physics, control, and all of the core topics of CPS into an enjoyable, integrated activity.

4.3 Course Project

The course project is designing a controller for an autonomous, three dimensional robot that can play ping pong (Figures 2 and 3). To introduce students to problem decomposition and iterative refinement, the project consists of building controllers under increasingly more realistic scenarios. In addition, the project includes a series of tournaments where players (controllers) developed by different teams directly compete in a simulated environment. The cooperative and competitive organization of the project is intended to highlight the importance of, as well as the challenges in, testing CPS designs. It is also intended to give students experi-

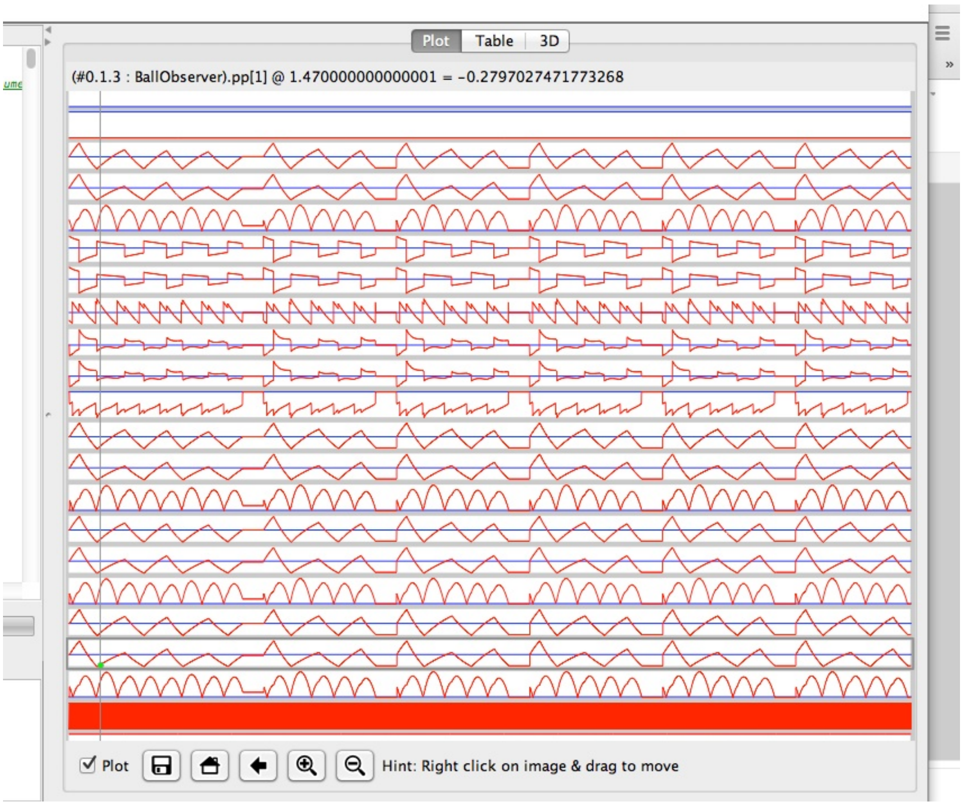

Figure 3: A ping pong playing robot as an example of CPS. This display shows only part of the state variables in the ping pong model used in one of the stages of the course project. The full state space is much larger.

ence with developing a complete system that must perform a complex, dynamic task whose specifications are defined only in high-level terms that may be hard to formalize.

Robot design is a good example of a CPS challenge for a number of reasons, including that it:

- Involves intimate coupling between cyber and physical components;
- Requires using hybrid and non-linear ODEs to model system behavior. In fact, even the simplest rigid body modeling of 2D dynamics introduces these complications;
- Raises non-trivial, open-ended control problems;
- Introduces embedded and real-time computation requirements; and
- Motivates the analysis of issues of communication, knowledge, belief, and intent.

Assigning students an ambitious project in a high-level modeling and simulation environment has several important benefits, including that it:

- Motivates the use of modeling and simulation in the CPS design process;
- Exposes students to the strengths and weaknesses of analytical techniques;
- Demonstrates the importance of developing extensive test scenarios as well as systematic experiments;
- Motivates the need for formal methods and tools by giving students first-hand experience with the limitations of testing;
- Allows students to run many more virtual experiments than physical experiments;
- Facilitates experimental measurement (and to some extent, evaluation) of CPS designs without constructing physical systems; and
- Reaffirms the value of collaboration, teamwork, and competition.

4.4 External Resources

External resources are included as embedded web links in the text of the lecture notes. Many of the references point to Wikipedia articles containing deeper discussions of topics mentioned in the course. Other references link to online video recordings relevant to CPS such as Lawrence Lessig's Threats to a Freedom to Innovate and Edward Lee's Heterogenous Actor Models.

5. Lessons Learned

In this section, we review and analyze the feedback from students in the first and second offerings of the course at Halmstad University. In addition to the formal student evaluations required for all courses at our University, we solicited informal feedback from students on specific exercises and labs, which proved very informative.

5.1 First Offering: Spring 2012

In the first offering of the course, we gathered some informal feedback from students during the last lab. Most of the feedback focused on Acumen and the project, including comments such as "it was fun to 'run' the design" and "support for 3D visualization was very useful." We also recieved explicit requests for "more intermediate exercises" indicating that we needed to expand our problem sets to introduce new concepts more gradually. When asked if we should make the project more challenging some students replied "the current project is difficult enough". A few students suggested simplifying the project, such as reducing the ping pong game from three dimensions to two dimensions. In addition, there were several suggestions for improving the Acumen syntax and user interface, as well as a request for a reference manual.

We were encouraged by positive feedback regarding the value of simulation illustrated with 3D visualization. Rather than retreating from 3D to 2D in the second offering of the course, we made a concerted effort to completely explain the 3D model and its interface. We also implemented most of the students' suggestions for improving the Acumen syntax and its user interface. We streamlined the course exercises, but are aware that we still need more intermediate exercises.

The formal student evaluations for the first offering of the course revealed a high level of satisfaction with the course as a whole. Eight students completed these reviews. Eighteen students took the class. Most students stated that the course required about 15-25 hours of studying per week (the target is 20 hours), but a sizable number said it required less than 15 hours, suggesting there is room for optional exercises. Student satisfaction with course materials (which consisted primarily of pointers to external reading materials) varied significantly. A free-form comment from one student stated that there was "too much reading on something easy". Satisfaction with examination forms (which included homeworks and projects) ranged from intermediate to very satisfied (top of the scale). All students either agreed that course objectives were completely met (top of the scale) or had no opinion (two students). Nearly all respondents were satisfied or very satisfied (top of the scale) with lectures, exercises, laboratory sessions, seminars, and assignments – with one student indicating an intermediate level of satisfaction with the lectures and exercises. Satisfaction with the information absorbed from the course was intermediate to very satisfied (top of the scale). On a scale from 1 to 6 with 6 being the highest, six students reported a level of satisfaction of 5, with one student reporting a level of 4 and the other of 6.

One experiment that was not an obvious success in the first offering of the course was teaching Lagrangian dynamics. While we aim to make another attempt at introducing this material in a later offering, the diversity of the student body suggested that a broader treatment of different classes of physical systems may deserve higher priority until we find an effective method for teaching this important approach.

5.2 Second Offering: Spring 2013

We also solicited informal feedback on the second offering of the course. At the end of the seventh lecture, we asked students to specifically provide feedback for this paper after telling them that an earlier draft of it had been accepted. The instructor suggested that students briefy identify which course items "worked" and which "did not work". After the instructor listed the various items on the board, we sorted them in terms of how strongly students felt about them. Items were sorted into three categories: #1 signifies most important, #2 signifies second most important, and #3 signifies other. In the process, students were allowed to update their opinions about various items. The following is a snapshot of the outcome:

Things that worked:

#1: The lecturing style – whiteboard with no slides, conversational, interactive – was highly regarded.

#2: Open access to all course material "was cool". We used Google docs for lecture notes and scribe notes (done collaboratively, in pairs, in real-time).

#3: The course introduction was inspirational and motivating; the assignments were enjoyable. Getting people to work together and help each other (on the project, homework assignments, and preparing for the final) was great and "made learning social". The supplementary reading and videos were fun. Students liked the fact that the class took a "comprehensive approach to the subject".

Things that did not work:

#1: There was a gap between the lectures, which were high-level and intended to motivate and engage students, and the course assignments. Students asked for homework assignments where each challenging problem is preceded by a sequence of easier problems providing clues on how to solve the difficult problem.

#2: Some open-ended problems included in the course assignment were too big and too hard to manage. The chapter on communications, which covers concepts of information, knowledge, belief, and truth, was too abstract, making it hard for students to determine what specific ideas they should master and remember. Students also suggested that it would help to devote more lecture time to discussing the course assignments and the course project.

A notable feature of the feedback on the second offering of the course was that it did not explicitly refer to either the project or the Acumen environment. Both were taken for granted as integral parts of the course. The students' discomfort with the chapter on communications may be due to the fact that the corresponding lectures cover epistemic topics in CPS and serve the purpose of introducing the subsequent topic of agent-based modeling.

We were encouraged by the feedback on the things that worked. In addition, many of the things that did not work confirmed the instructors' impressions of the course and helped formulate concrete action items for revising future editions. The instructors gave three unplanned tutorial sessions to help students with their assignments and project in response to this feedback.

The feedback on course materials for the second offering of the course was better than for the first, presumably because we expanded the chapters in the lecture notes from outline to expository form. We also reduced the amount of assigned reading and made a clear distinction between required reading (which became the lecture notes) and rec-

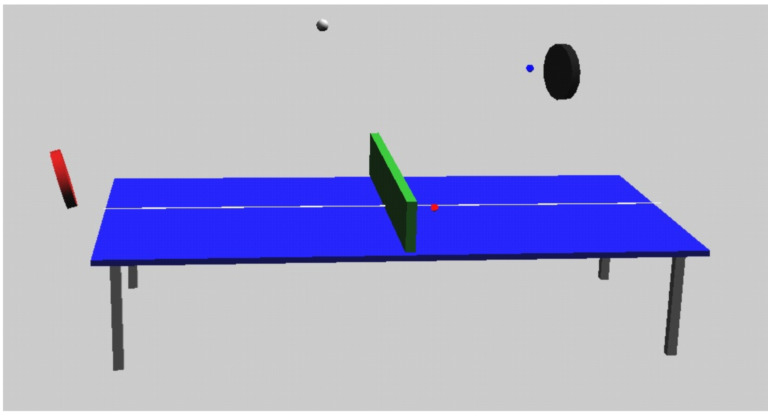

Figure 4: Convenient 3D visualization, which is crucial for virtual CPS design and testing. Yingfu Zeng's Master's thesis [8] showed that it is possible to conveniently integrate mathematical models of hybrid systems (such as those used in Acumen) with 3D visualizations by inserting "3D probes" directly into the models. The probes are concise statements. Experience so far indicates that they are easy to maintain.

ommended reading.

Based on student feedback and our experience with the two offerings of the course, we believe that we have shown that:

1. Hybrid systems can be used effectively as a unifying framework for modeling a wide variety of cyber-physical systems;
2. Simulation is very helpful in bringing hybrid automata to life;
3. Animated simulation for virtual experimentation engages students;
4. Assigning a project in which the students focus on designing a robot and evaluating its performance using a simulated environment that supports 3D animation enables a diverse student population to master core principles of CPS design;
5. Using competitive games including a semester-long tournament engages students; and
6. Support for 3D visualization facilitates CPS design and makes ambitious design projects accessible to a broad population of students.

6. Status, Excluded Topics, and Plans

Our current CPS course is required by one of three tracks in the masters program in Embedded and Intelligent Systems (EIS) at Halmstad University. Starting in Fall 2013, it will be a required first-semester course for *all* students in the EIS masters program. Our ultimate goal is to move this course to earlier in the curriculum, first to the advanced undergraduate level and perhaps to the second year (sophomore) level, depending on a student's level of preparation before entering college.

Every course syllabus makes implicit choices about what material to exclude from a course. In our case, we chose not to include linear systems (of ordinary differential equations), mathematical models based on complex numbers, or an introduction to the wide range of computational and simulation tools supporting CPS design. This is not to say that these topics and tools are not important. Rather, we chose to exclude them because the core principles of CPS can be taught in the context of a single high-level environment (Acumen) and there are numerous excellent discussions of these topics in the literature, enabling students to assimilate them independently as needed after completing a first course.

However, there are topics not included in our syllabus that we would like to add to our core CPS curriculum. For example, the chapter on Modeling Computational Systems focuses on justifying the fundamental physical characteristics of computational components, how they interact with the surrounding world, and the difficulties that arise when we try to use them to implement continuously modeled components (typically controllers). We are working on expanding this section to cover more concrete aspects of embedded and real-time software design as presented, for example, in the recent textbook of Lee and Seshia [5]. We are developing materials that add the basic concepts from Lee's Models of Computation to the chapter on Modeling Physical Systems to prepare students for subsequent exposure to these topics in other courses. We expect that this addition will both enrich the course and make Models of Computation accessible to a broader audience.

In our experience, a major challenge in creating a new course is devising accessible exercises that embody the concepts introduced in lectures. Currently, we introduce vector algebra in the chapter on Modeling Physical Systems. We plan to introduce more material on geometric modeling in this chapter, and anticipate that this addition will help students distinguish modeling system geometry from modeling system dynamics and gain more facility with vector algebra.

In terms of environment development, we plan to extend Acumen in the near future to support expressing uncertainty in models and simulations. We plan to develop a library of composable basic components that would allow students to virtually experiment with building systems from components. We believe that such a library would provide a framework for teaching a wide range of principles and skills that are important in CPS design. On a more concrete level, we are developing a socket-based interface that exposes the

Figure 5: The Tournament, a semester-long project that engages students.

entire state of the simulated system to other tools such as Ptolemy II, MATLAB, and LabView. We are also exploring the possibility of supporting the Functional Mockup Interface (FMI) [4] under development by Daimler AG and other companies and research institutes.

7. Conclusions

There is significant agreement in the CPS community on the need for better CPS curricula. A major challenge in forging such a curriculum is accommodating a student population with diverse educational backgrounds. To address these issues, we have developed and offered a first course on CPS that relies on a simple high level modeling and simulation language embodied in an interactive environment supporting 3D visualization. This paper describes the course, and includes a statement of desired educational outcomes, a proposed selection of core CPS topics, an outline of the course organization and materials, and lessons learned from the first two installments of the course. The course employs openly available resources, including lecture notes, a modeling and simulation environment (Acumen), and links to other external resources. It makes extensive use of virtual experimentation and visualization to enrich and accelerate the learning of concepts introduced in lectures in a practical and cost-effective manner. Experience with the course has been positive. Students taking the class came from undergraduate programs around the world and appear to have benefited uniformly from the course. A decision has been made to make it a required, first-semester course in the Embedded and Intelligent Systems (EIS) masters program at Halmstad University.

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