Developing A First Course on Cyber-Physical Systems * †

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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 of 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 four 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 difficult to explain to students why CPS design is technically challenging and to identify tools and methods to empower CPS developers to overcome the technical problems involved in creating new systems.

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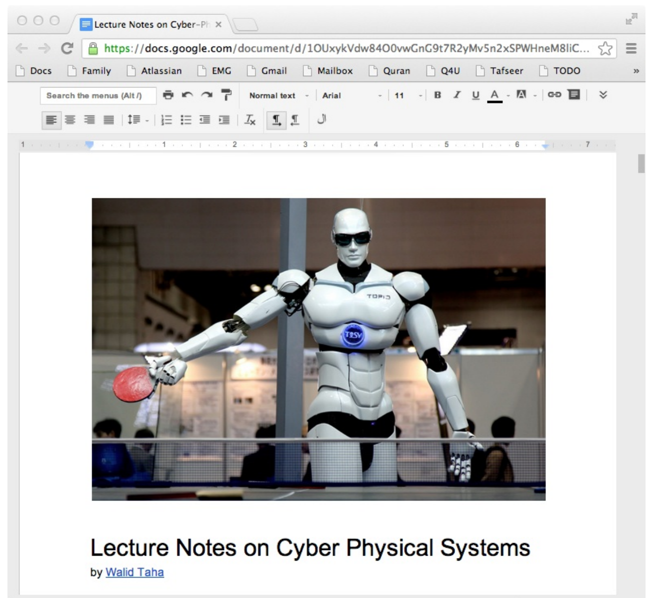

Figure 1: The lecture notes [11] are freely available online under a Creative Commons license.

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 the development of 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 those countries are comparable.

All materials developed for our course are freely available under appropriate open licenses. The living (and continually evolving) lecture notes are available online [11] under a Creative Commons license (Figure 1). A portable distribution (based on the Java Virtual Machine, or JVM) of Acumen, an interactive modeling and simulation environment used in the course, is free and is available online [2] under a BSD 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 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 [11] 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. Game theory.

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. In order 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 community. 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, within the context of an ongoing NSF CPS project on Robot Design. The professors 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 game theory as a core topic of CPS was motivated by its utility in addressing notions of cooperative and competitive behavior. Its 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 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

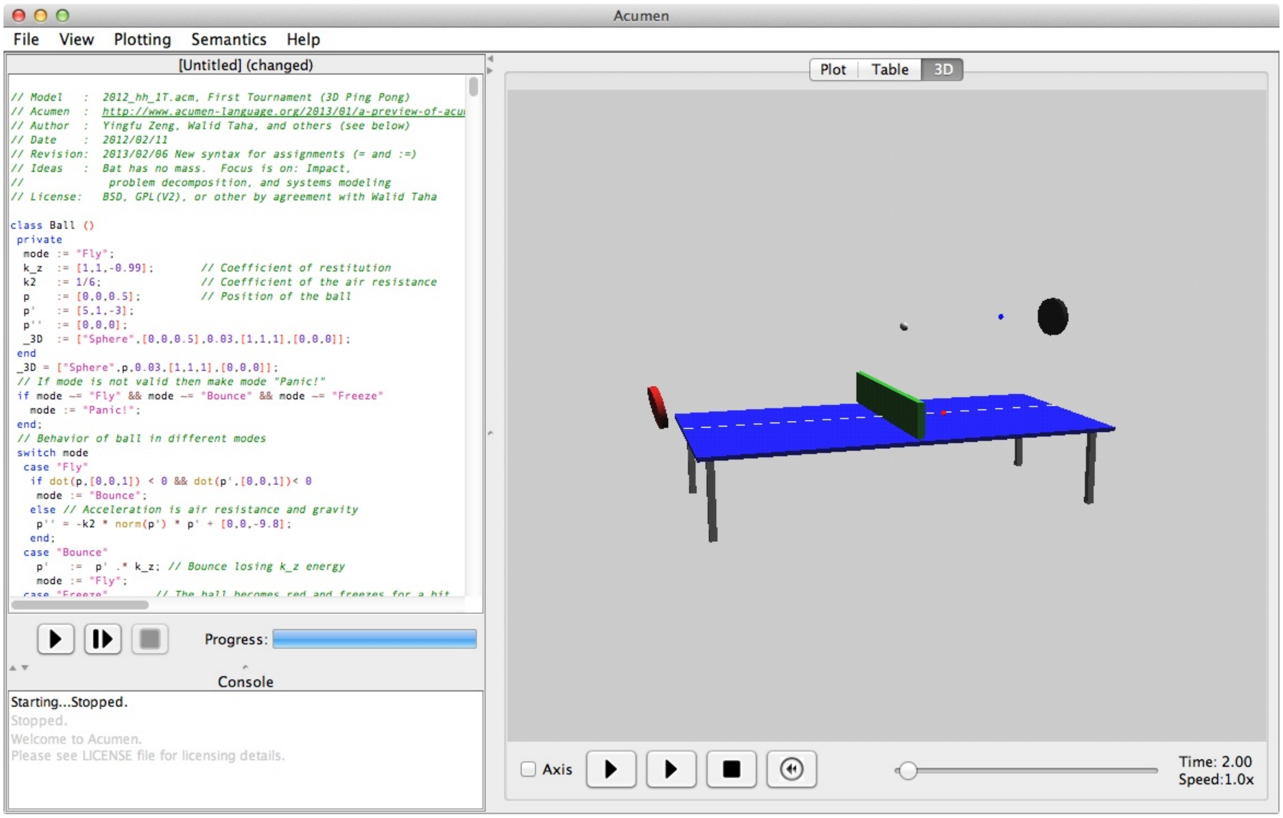

Figure 2: Acumen, a free open source hybrid-systems modeling and simulation environment used to teach CPS.

The modeling and simulation environment used in the course is Acumen [2, 13], an interactive environment for modeling distributed dynamic hybrid systems. It is used in the course project, laboratory sessions, and some of the homework assignments. Acumen is a development environment and interpreter for a small textual language, which 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, the core formalism that students learn from some canonical examples 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 encourages 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 and integrated activity.

4.3 Course Project

The course project is to design 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 requires the building of controllers under increasingly more realistic scenarios. In addition, it 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 experience with developing a complete system that must perform a complex, dynamic task, where the 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

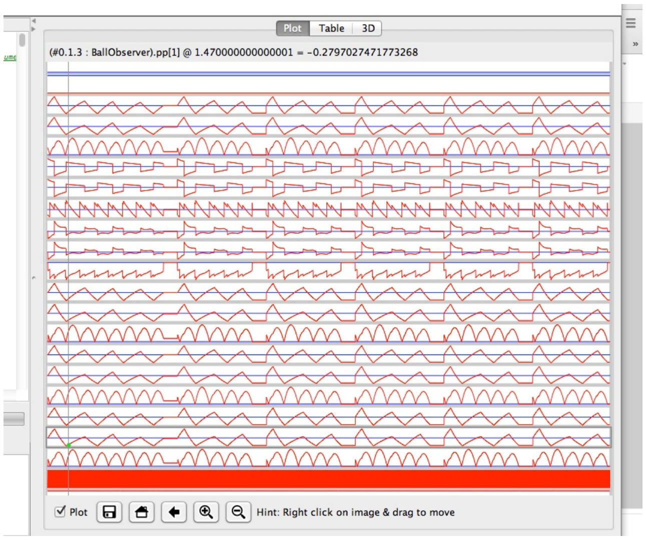

Figure 3: A ping pong playing robot as an example of CPS. This display shows only part of the state variables in the ping pong model used in one of the stages of the course project. The full state space is much larger.

- 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;
- Illustrates 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 would be possible with 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 received 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. Additionally, we streamlined the course exercises, but were aware that more intermediate exercises were still required.

The formal student evaluations for the first offering of the course revealed a high level of satisfaction with the course as a whole. Eight of the eighteen students who took the class completed these reviews. 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 that there was room for optional exercises. 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; one student indicated an intermediate level of satisfaction with the lectures and exercises. Satisfaction levels with the information absorbed from the course ranged from intermediate to very satisfied (top of the scale). On a scale from one to six, with six being the highest, six students reported a level of satisfaction of five, with one student reporting a four and the other a six.

One experiment that was not an obvious success in the first offering of the course was teaching Lagrangian dynamics. While we will aim to reintroduce 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.

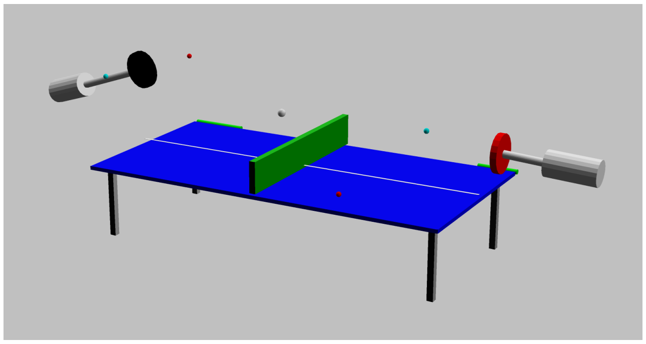

Figure 4: Convenient 3D visualization, which is crucial for virtual CPS design and testing. Yingfu Zeng's Master's thesis [14] showed that it is possible to conveniently integrate mathematical models of hybrid systems (such as those used in Acumen) with 3D visualizations by inserting "3D probes" directly into the models. The probes are concise statements. Experience so far indicates that they are easy to maintain.

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 an earlier revision of this paper. The instructor suggested that students briefly 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 more difficult one.

#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 we got 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 appeared to be aresult of the focus of that edition of on epistemic logic topics in CPS which was partly intended as an introduction to a subsequent chapter of agent-based modeling. More recently, that material was excluded and agent-based modeling has been replaced with an introduction game theory.

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 recommended reading.

5.3 Third Offering: Winter 2013

There were several significant changes with the third edition of the course. It became a required component of the Masters program and was made available as an optional course for advanced undergraduates. Course attendance rose to about 50 students. As a result of this size increase, not only was the content development continued, but several administrative changes were made with the goal of facilitating the management of this larger class; a chapter on game theory was introduced as the material for the last (eighth) week; the chapter on communications was changed to focus on more information theoretic aspects of communication channels; the Acumen syntax was improved; a manual was included with the distribution; several changes were made with the goal of accommodating the larger class size; the scribe role was eliminated; the lectures were recorded for students to use during the semester (although they ended up not being ready until very late in the course) and for use in future editions; a learning management system (Blackboard) was used, as well as a tool for collecting and answering student questions (Piazza). Finally, because of the volume of students and the existing lab spaces, it was also necessary to split the lab sessions into two groups, one taught by the main instructor and the other taught by two co-instructors.

At the end of the third offering of the course, informal feedback was solicited from the students in essentially the same way as at the end of the second offering. In this instance, students were first asked to list items that could be classed under "What was Good?" and, once that was complete, they detailed "What can be Improved?". There was much more feedback than in previous years but, unfortunately, the instructor forgot to ask the students to prioritize the issues.

The items that students suggested for “What was Good” included:

- Having assignments.
- Notes (Suggested improvement: add recommended models and more examples in Acumen).
- Tournament was a nice idea.
- The best thing about Acumen is the 3D part (3D objects very easy).
- Keep the [parts about] physics, especially the modeling.

The items that students suggested for “What can be Improved” included:

- Game theory overlaps with AI [course] (The student who suggested this later sent an email retracting it).
- Faster feedback on assignments.
- Grading policy percentages needed clarification.
- Assignments [are] a bit too much in the [second] half of the semester.
- Big gap between lectures/notes and assignments. (Suggestion: more time in class?)
- Acumen models confused with programs at the start. (Suggestion: more exercise/explanation about loops/fixed-point semantics).
- Calculus and basic physics (Would like more advanced materials instead).
- Big discrepancy between labs.
- Installation manual needed for Acumen, or generating an executable (3D function).
- Acumen was slow.
- Different semantics [for Acumen were] distracting.[1]
- Didn’t understand the ping pong model when the tournament started. Some smaller Acumen problems would be nice.
- No debugging support in Acumen (Examples: expression evaluation, printing facility).
- Would like to have line numbers in error messages.
- It would be nice to have error codes explained in more detail in the manual.

Some (though not all) of these criticisms were echoed in the students’ formal evaluation forms, which raised the following main issues:

- Unfamiliarity with Acumen as a reason for many trivial tasks taking longer than necessary.
- High workload (coupled with high workload in the other course that must be taken in parallel).
- Mixed responses to how well the course helped clarify the connection between the topics that make up CPS.
- A need for more lectures and coverage of more material in lectures, especially focusing on the advanced rather than introductory aspects; more examples in the lectures too.
- A gap between lectures and the homework assignments.
- Slow feedback on assignments.

It is our opinion that many of these difficulties surfaced because of the increase in class size. In particular, the first two editions of the course were executed in an instructor-intensive manner, where the instructor worked closely with the students to overcome any shortcomings in the notes, lectures, or tools. The increase in the size of the course was unexpected; what made things worse was that the first estimates (one month before the start of the course) indicated that the incoming class would comprise around 80 students. This led to many changes (listed at the start of this subsection) intended to deal with the increase in size. Many of these changes (Blackboard, Piazza, recording lectures, dropping scribe notes) had the effect of isolating the instructor and the student, making it more difficult to identify and address issues as they developed. As a result, the instructor learned about many of them only at the end of the semester.

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

5.4 Fourth Offering: Winter 2014

Based on the feedback from the third offering, the main change in the fourth edition was to use the video recordings made in the previous year to offer the course in a flipped-classroom [7, 4] format. In this rendering of the flipped-classroom model, students watched the lecture videos, did the reading, took an online quiz, and then came to class. In class, students worked on pre-determined problems. This was a deviation from an earlier plan to cover advanced material in class, and was inspired by a talk by David Black-Schaffer on Flipping the Classroom in an Introductory IT Course [5]. We experimented with both group and individual problems (Figure 6 portrays a group exercise). The use of the online quiz before class was inspired by Peter Marwedel’s remarks at WESE’14 about the risk of students delaying the watching of lectures until it is too late in the course. As a further measure to reduce this risk, the lecture videos were only made available before class time.

To support classroom activities in the flipped-class room model, we developed a simple system for pseudo-random seat allocation. This consisted of using cards that were printed ahead of class time and given to students as they entered the classroom. The cards assigned seats so that, firstly, students arriving together were seated at distant locations and, secondly, the chance of students being paired in groups of two was increased.

Other changes to the course included:

[1]Only one semantics is used in the course. What seemed to cause the confusion here was that the GUI allowed the user to select legacy implementations.

Figure 6: In the flipped-classroom, we experimented with both group and individual problems.

- Changing the grading scheme to allow students to, in principle, make up any grade points lost in year work by means of a sufficiently high grade on the final. We achieve this by taking the final grade be the maximum of either the grade on the final or the weighted average of coursework and grade on final. Using this rule makes the grades collected from course work become just one of two ways of getting grade points. This change reduces the cost of make-up exams, which the school is required to offer to students.
- Reducing the frequency of project tournament deliverables.
- Staffing the course to ensure that assignments are graded and returned quickly to students.
- Making the grading criteria and policy more transparent in the lecture notes.
- Adding more practice exercises. In some cases these were based on past exams; in others they were custom-made for the classroom study-problem sessions.
- Making more explicit the role of the project in illustrating the connectedness and the need for the various sub-topics of CPS .
- Adding more solved examples and Acumen examples to the lecture notes.
- Reducing the number of topics and strengthening the connections between them rather than making additions. As a temporary measure the chapter on communications was not covered in the this edition, though there remains a plan to reintroduce it once the workload from the other chapters has been successfully reduced.
- Extensively updating Acumen to address the specific issues that students identified in the previous edition of the course.

Student feedback was collected through weekly surveys about workload, a discussion at the end of the course, and through the university's student evaluation forms. Weekly surveys indicated that the workload was much more manageable than in the previous year, although it appeared that another course taught at the same time produced an excessive workload. In the end-of-term discussion, after students has made their suggestions for "What Worked" and "What Could Be Improved", they were asked to vote on the importance of the various suggestions. There were 24 students in attendance during that session, but it was noticed that some students voted with both hands for issues that they were particularly enthusiastic about.

Things that worked, with the number of votes shown in parenthesis:

- Flipped classroom works very well (25)
- Reading materials in general (23)
- Teacher reaction to questions was encouraging (23)
- Random seating arrangement was perfect (21)
- Study problems worked very well (20)
- Quiz being time limited (20)

Things that can be improved:

- There was no notification on quiz answer availability (22)
- More feedback on study problems - maybe also solutions (20)
- Lecture recording video quality for things on board (17)
- Student questions/answers in videos are not audible (13)
- Maybe form teams randomly (10)
- Can be hard to hear other student questions (9)
- More feedback on project (9)
- Forming teams was a bit difficult/tricky (7)
- Enable backtracking in quiz - helps deal with network connection problems and managing the time limit (7)
- Can't see equations in RTF or PDF when you download notes (6)
- Maybe change teams/divisions during the course (5)
- It can get a bit noisy in class - until the last few weeks (3)
- There are Acumen-specific things in the videos with the old syntax (-)
- It would be nice if there was a way to ask questions during the video (-)

Many students were initially suspicious of the flipped-classroom model, and it was encouraging to see most opinions reversed by the end of the course. Also, compared to an average grade of 40% on the final exam in the previous year, the average grade was 46% this year. An effort was made to make the exams comparable, and it was reassuring that changing to the flipped-classroom model did *not* lower performance on the final exams. The number of students matriculated rose from 42 to 57 and student satisfaction rose from 59% to 73%.

It was also encouraging that most areas where students felt that there was room for improvement appeared tractable. Based on this student input and our experience from this edition of the course, for the next edition we plan to:

- Review the LMS-related issues to streamline the use of online quizzes.
- Investigate a more nimble mechanisms for the weekly survey.
- Create more large-team student problems for the in-class study problems. Our experience in the last edition suggests that it may be most beneficial to students to work in large teams in the first part of the lecture and then on individual problems in the second.
- Raise the bar (and communicate its requirements to students) for each round of the tournament. It was felt that in this edition of the course students opted for completing the minimum requirements for getting the grade rather than for developing competitive players.
- Develop infrastructure to support the project tournaments.This functionality should include automating team creation, grading (see for examples [8, 9]), and tournament management. If there is an efficient way to build teams, we may explore the possibility of rebuilding teams each week.
- Improve the video recordings to overcome the difficulties identified by the students.

Thanks to the support of Halmstad University and the Swedish Knowledge Foundation (KK), resources are available to make these valuable adjustments and part of the work is already underway.

5.5 Self Assessment

Based on student feedback and our experience with the four 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;
6. Support for 3D visualization facilitates CPS design and makes ambitious design projects accessible to a broad population of students; and
7. The flipped-classroom model is not only more scalable to larger classes (which we had assumed to be over 100) but may also be more conducive to student engagement at moderate class sizes (40-50 students).

6. Status, Excluded Topics, and Plans

Our current CPS course was initially required by only one track in the Masters program in Embedded and Intelligent Systems (EIS) at Halmstad University. Starting from the Fall of 2013 it became a required first-semester course for *all* students in the EIS masters program. Since its second offering it has been open to senior undergraduate students. From 2015 it will be offered in a condensed format as a short course for PhD students. One of our ambitions is to develop editions of this course that can be taught at lower levels, first to advanced undergraduates and perhaps to the second year (sophomore) students, depending on the student's level of preparation before entering college. We also hope to expand the offering to other programs at the university.

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.

There are also topics not currently 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 [10]. 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 the expression of 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 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) [6] 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 achieving this 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 its desired educational outcomes, a proposed selection of core CPS topics, an outline of the course organization and materials, and lessons learned from the first four 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. Experiences with the course have been positive. Students taking the class have come from undergraduate programs around the world and appear to have benefited uniformly from it. In the third edition, the most significant challenge appeared to be the increase of class size to near 50 students. This reduced the level of direct contact between the instructor and the students, in turn reducing the capability of the instructor to assess and manage the level of difficulty of the material, and to compensate for any shortcomings in the evolving content and tool support. The measures we employed to address this challenge are outlined, as is the result of applying them in the following (most recent) year. We employed the flipped-classroom model with encouraging results. In the near future, development efforts will focus on making better use of technology and improving the available content and tools to explore the extent to which this approach can provide an excellent education in the principles of CPS to students from as broad a background as possible.

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References

[1] Cyber physical systems. Course Syllabus adopted by the School of Information Science, Computer and Electrical Engineering, Halmstad University, Sweden, 2011. http://bit.ly/DA8003.

[2] Acumen web site. http://www.acumen-language.org, 2012.

[3] Bologna process (Wikipedia). http://en.wikipedia.org/wiki/Bologna_Process, 2012.

[4] Jacob Lowell Bishop and Matthew A Verleger. The flipped classroom: A survey of the research. In *ASEE National Conference Proceedings, Atlanta, GA*, 2013.

[5] David Black-Schaffer. Flipping the classroom in an introductory IT course. KTH Media Production. http://youtu.be/57MvwhSbv3k, 2013.

[6] Torsten Blochwitz, Martin Otter, Johan Åkesson, Martin Arnold, Christoph Clauss, Hilding Elmqvist, Markus Friedrich, Andreas Junghanns, Jakob Mauss, Dietmar Neumerkel, Hans Olsson, and Antoine Viel. Functional mockup interface 2.0: The standard for tool independent exchange of simulation models. In *9th International Modelica Conference*, Munich, Germany, September 2012.

[7] Clyde Freeman Herreid and Nancy A Schiller. Case studies and the flipped classroom. *Journal of College Science Teaching*, 42(5):62–66, 2013.

[8] Jeff C Jensen, Edward A Lee, and Sanjit A Seshia. Virtualizing cyber-physical systems: Bringing cps to online education. In *Proc. First Workshop on CPS Education (CPS-Ed)*, 2013.

[9] Garvit Juniwal, Alexandre Donzé, Jeff C Jensen, and Sanjit A Seshia. Cpsgrader: Synthesizing temporal logic testers for auto-grading an embedded systems laboratory. In *Embedded Software (EMSOFT), 2014 International Conference on*, pages 1–10. IEEE, 2014.

[10] Edward A. Lee and Sanjit A. Seshia. *Introduction to Embedded Systems, A Cyber-Physical Systems Approach*. http://LeeSeshia.org ISBN 978-0-557-70857-4, 2011.

[11] Walid Taha. Lecture Notes on Cyber Physical Systems (LNCPS). http://bit.ly/LNCPS-2014, 2014.

[12] Walid Taha, Robert Cartwright, Roland Philippsen, and Yingfu Zeng. Experiences with a first course on cyber- physical systems. In *2013 Workshop on Embedded and Cyber-Physical Systems Education (WESE)*, Montreal, Canada, 2013.

[13] Walid Taha and Roland Philippsen. Modeling basic aspects of cyber-physical systems. In *Workshop on Domain-Specific Languages and Models for Robotic Systems (DSLRob)*, 2012.

[14] Yingfu Zeng. Lightweight three-dimensional visualization for hybrid systems simulation. Master's thesis, Halmstad University, Halmstad, 2012.