Final Lab: Star-Lab
15-424/15-624 Foundations of Cyber-Physical Systems

Whitepaper Due Date: **Friday 11/07**, worth 20 points
Proposal Due Date: **Monday 11/17**, worth 80 points
Final Project Due Date: **Friday 12/05**, worth 100 points
Term Paper Due Date: **Friday 12/05**, worth 100 points
Presentation Due Date: **Wednesday 12/10**, before the CPS V&V Grand Prix

The 15-424/624 final project (star-lab) is an opportunity for you to creatively use what you've learned throughout the course *Foundations of Cyber-Physical Systems* and dive deeply into a CPS problem of your choosing. It is your big chance to achieve fame, glory, and prizes at the CPS Verification and Validation final project competition (**CPS V&V Grand Prix**).[1] What you attempt for your project is completely up to you and your potential team-mate. There are only two requirements: (1) We want your project to be challenging (you should learn something relevant to the themes of this class) and (2) we want your project to be fun (you should be pumped to work on it)!

Choosing a Project. The most common way to choose a project is to design, model, and verify a cyber-physical system in an application area that is interesting to you. The system you decide to model and how you design it is entirely up to you, but we *strongly recommend* you tackle problems that can be simplified in multiple ways. This way, the simpler versions can be used as stepping stones for the understanding of the full, complex problem. If this full problem becomes too difficult, those stepping stones work as deliverables, and you discuss the challenges faced in the term paper.

The canonical project follows the lab format of: design a hybrid program, determine reasonable safety/liveness properties, prove those properties using KeYmaera. But other options are possible. Other project ideas could focus on developing a simulation or design tool for cyber-physical systems, or on implementing a verified CPS model on a hardware platform.

Coming up with a project is up to you. For inspiration, there is the list of previous projects from 2013[2], and some extra suggestions that might lead to successful projects. Don't let them limit your imagination though!

- Proportional-integral-derivative (PID) controllers.
- Insulin pumps, pace makers, or other medical devices.
- A thermostat which controls one or more rooms.
- Electrical circuits.
- Chemical reactions.
- Biological systems, for example predator/prey systems.
- Use $\mathsf{d}\mathcal{L}$ to solve the duck and fox interview question (link).

[1] CPS V&V Grand Prix `http://symbolaris.com/course/fcps14-competition.html`
[2] `http://symbolaris.com/course/fcps13-projects.html`

- The Knight Rider signature move (link).
- Extend the later labs in significant ways, e.g. by adding noisy sensors, extra obstacles, better distance measures, etc.

White Paper: The white paper will set up some preliminary ideas regarding the topic, scope and challenges of your project. Here are some topics that should be discussed.

- A generic description of the hybrid system you propose to study for the final project, and how you intend to model the hybrid system. *Cite any references you intend to use as source material.*
- Propose a hierarchy of progressively more complex models of your system, which could be used as stepping-stones to more complex models or controllers. These can include more realistic modeling of the CPS as well as increasingly better controllers. This step is optional, but *strongly recommended.*
- You should discuss the core properties that guarantee the correct functioning of the system (for example, safety and liveness) and how you intend to prove or analyze the fulfillment of these properties.
- For properties you intend to prove using KeYmaera, discuss how you intend to approach the proof (for example, you might propose loop or differential invariants or explain how you might manage branching).
- Identify expected challenges to solicit feedback.
- Identify expected deliverables, i.e. what the output of your project is going to be. These can be, for example, .key files and their proofs.

The white paper should be **formatted as a pdf** and be roughly 1 to 2 pages long. The intent of the White Paper is for you to get feedback on your ideas and how feasible they are, so that you can adapt it for the Project Proposal.

Project Proposal: the project proposal is a fleshed out version of the White Paper. The proposal will help you organize your thoughts about your project and will give the course staff a chance to check that your plans are of the right scope and provide suggestions and advice. As applicable, the proposal should contain the following:

- A description of the system and why you think it's interesting and relevant.
- A discussion of the desired properties for the system (formalized in $\mathtt{d}\mathcal{L}$, if appropriate), and why they are relevant and important, e.g. safety, efficiency.
- A detailed exposition of related work to show how the problem you are proposing relates to the state of the art.
- A detailed description of each stepping stone for the problem, including how you plan to tackle them, and why they are easier than the more complex problem.
- Each goal and "deliverable" in your project *should be clear.*
- If appropriate, .key files for each stepping stone, which includes the controller, the CPS modeled as a hybrid system, and the relevant property.
- Reports on the progress of the proofs and identification of the technical challenges you are facing and how you have solved them.

The primary purpose of the project proposal is to justify why the problem that you are solving is interesting and concisely describe the challenges.

Remember that the stepping stones are optional but highly encouraged. They increase the probability you will have something to deliver, and that's always a good thing!

Final Project: The final project should be a zip file with all your deliverables. These can include code, as long as it is easily compilable (e.g. use a Makefile), and all the .key and .proof files that are relevant. The use of comments in hybrid programs is encouraged.

Project Paper: The project paper should discuss the achieved results in some depth, and compare them to what was originally proposed. There should also be a discussion of the challenges faced and how they were, or not, overcome, as well as any ideas on how to tackle them for the future. It should be about 12-16 pages long.

The project paper should be structured like a scientific paper. This requires a bit of a paradigm shift from typical project reports! Imagine that you are presenting your findings to a panel of *very busy experts* in the area. You'll need to *engage them quickly*, and convince them of the value of your work. To do so, you should very clearly *outline your contributions* to the field of CPS verification. Make it sound exciting by *highlighting all the potential applications* and by illustrating how you are *pushing the state of the art*. Even if they didn't result in a .proof file, your insights are valuable! Share them, and explain their relevance.

Remember that CPS experts aren't necessarily familiar with $\mathsf{d}\mathcal{L}$ or even the logic-proof approach in general. You should take care to *ensure that they can follow your explanation* of the verification results (e.g. the safety proof). This includes giving the best intuitions that you can regarding what invariants are, how you came up with yours, why they are relevant, and how they helped the proof.

Make sure to *deflect any potential criticism* by defusing worries the reader might have (e.g. by explaining why a simplification of your model is actually OK) throughout the entire document.

You are highly encouraged to pick up a published paper on CPS verification to get a feel for how they are written. Picking something related to your specific topic would be a plus, but not absolutely necessary.

The final paper should contain:

- A brief abstract summarizing the goals and findings of your project.
- An introduction explaining your project and justifying why it is both interesting and a challenge. Include a discussion of how your project relates to the state of the art, preferably as a separate related work section.
- A related work discussion is not a discussion limited to where someone has done exactly the same problem before. If that were ever the case, you need to look for a new project, because the problem is solved. Related work is supposed to talk about *related* aspects.

Discuss things that have some resemblance or similarity with what you are doing and explain how your project differs. If you have built your project on existing models or code or approaches, please mention and cite where they came from and discuss the relation to your project. A thorough discussion of related work as well as references to all prior work that your project is based on will be one component of the evaluation of your project paper.

- A detailed explanation of the approach you took for your project. This includes in-depth (but not verbose!) descriptions and justifications of the CPS models and properties that you have studied.
- You have to carefully justify and explain all your models and properties. You need to justify why your models are the right models and why you have reached the right accuracy and analyzability tradeoffs, i.e. studying a system so complex you can't prove it versus studying a system so simple it's not realistic enough for actual use. Unjustified models and properties or models whose differential equations and control principles have not been explained will be ignored in the evaluation of your project. For all simplifying assumptions in your model, justify to what extent and under which circumstance they are reasonable and explain where they help you. This is also applicable for your differential equation domains, control conditions, etc.
- Describe and explain how you proved the properties. You should provide a brief proof sketch in which you describe how you structured the proof, what invariants and differential invariants you used, and which other important ideas went into your proof, such as steps for taming the arithmetic.
- Consider illustrating the problem as well as the intuition for important aspects of your solution by graphical illustrations. It is helpful to include relevant illustrations that you are planning to for the purposes of your project presentation.
- Conclude with a discussion of what you have learned about the problem you set out to tackle in your project. Describe how what you achieved relates to the goals you set in the proposal. If some goals were not met, explain why. If you achieved goals that you had not planned on, identify them and point out what experience during the project made you consider these goals.
- Summarize the project deliverables
- If you use LaTeXto write your term paper, BibTeX is your friend for managing citations and references and DBLP is a good source for bibliographical entries.
- It is okay to reuse (and revise) material from your proposal for the term paper if it is still accurate.
- If your project is a team project, please list the work performed by each partner. If you do not feel comfortable making this information publicly available, you may email the course staff this information directly. Alternatively, you can simply state: "equal work was performed by both project members."
- Finally, you should make sure that your project paper provides enough context and information and careful explanation to enable the course staff, reviewers, and judges to fully understand and appreciate the value of your project.

Project Presentation: Your final project presentation on Wednesday December 10, between 1:00 and 5:30pm, at the CPS V&V Grand Prix. This is arguably the most important part of your project!

You will have exactly 10 minutes to talk through the slide presentation about your project to a panel of industry experts from such companies as Bosch, MapleSoft, Toyota, Reactive Systems, MathWorks, Intel, GM, and Google. It is a *unique opportunity* for you to showcase your CPS verification skills to people who are interested in them for real-world products and applications! Because you will be competing in the CPS V&V Grand Prix, you have exactly 10 minutes for your presentation and, in the interest of fairness, will be cut off when the time is up.

Much of the advice about project papers continues to apply to the project presentation. In addition:

- The talk should be split into the introduction that explain the background and significance of the problem you solve, the middle part detailing the approach you took to solve the problem, and a presentation of the results as well as a summary.
- Thoroughly explain the significance of your project and give sufficient background and potential application areas.
- Highlight what is important about your project.
- Identify contributions, results, and outcomes of your project. Be sure to identify all major conceptual and technical challenges you solved.
- You should place a strong emphasis on an intuitive exposition of your project and make use of visualizations and graphical illustrations supporting your project.
- Slides with too much text are not an effective way of getting the attention of the audience.
- When including models and formulas on your slides, make sure they are properly typeset and discuss their intuition.
- You should practice your talk often and time yourself to ensure you communicate effectively within the allotted time slot.
- Finally, you should make sure that your project paper provides enough context and information and careful explanation to enable the course staff, reviewers, and judges to fully understand and appreciate the value of your project.

When you are preparing the slides for your talk, you may learn what intuition you should add to your project paper. When you give detailed explanations and elaborations in your project paper, you may learn what aspects are important to retain in your project presentation.

All slides and material for your project presentation is due before the CPS V&V Grand Prix.