Final Lab: Star-Lab
15-424/15-624/15-824 Foundations of Cyber-Physical Systems

Whitepaper Due Date: **Tuesday 03/29**, worth 20 points
Proposal Due Date: **Tuesday 04/05**, worth 80 points
Final Project Due Date: **Tuesday 04/26**, worth 100 points
Term Paper Due Date: **Tuesday 04/26**, worth 100 points
Presentation Due Date: **Thursday 05/05**, before the CPS V&V Grand Prix

The 15-424/624/15-824 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 teammate. 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 that you have faced during the project and explain the technical why that happened in your 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 previous years[2]. Don't let them limit your imagination though!

White Paper: The white paper will set up some preliminary ideas regarding the topic, scope and challenges of your project. You should think of the white paper as pitching your project idea to a funding agency or possible investor in a written analogue of an elevator pitch for the purpose of giving them a chance to see whether there is any interest in what you are suggesting. It is crucial that you communicate concisely and clearly what exactly

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

[2] `http://symbolaris.com/course/fcps13-projects.html`
and `http://symbolaris.com/course/fcps14-projects.html`

you are planning to do, why that is a good idea, where you expected challenges and how you plan to master them. 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 and properties 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.
- 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 X, 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, .kyx files and the tactics of 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. Keep in mind that our feedback on your white paper cannot be effective if your white paper does not effectively communicate what you are trying to achieve.

Project Proposal: the project proposal is a fleshed out version of the White Paper. It will give you a chance to report on what you have achieved with your research since the White Paper, what exactly you are planning, what technical challenges your research identified, and what solutions you are planning to overcome them. 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 descriptive title for your project and your names and email addresses on the proposal. Maybe you should do a brainstorming session to find a strong descriptive title communicating your project clearly.
- A description of the system and why you think it's interesting and relevant.
- A formal model of the system you are considering and a precise explanation and justification of its model.
- A discussion of the desired properties for the system (formalized in $\mathsf{d}\mathcal{L}$, if appropriate), and why they are relevant and important, e.g. safety, efficiency.
- Informal explanations why each of the assumptions you make is necessary or useful for the properties you are trying to prove and informal arguments why you do not expect other assumptions to be needed (mind the Cartesian Demon).

- A detailed exposition of related work to show how the problem you are proposing relates to the state of the art in the science of cyber-physical systems.
- 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, .kyx 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 are planning to solve them or have solved them already.
- Figures can be helpful for illustration purposes. Even if you focus on one particular motivating application, you should broadly discuss where else your findings have applications.

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

Remember that stepping stones are 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 .kyx models and .kyt tactics and .kyp 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 sufficient depth to assess your work, 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 and validation. 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 your application question, 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/differential invariants are, how you came up with yours, what they mean intuitively, 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 is 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 as a separate related work section.
- A detailed explanation of the approach you took for your project. This includes in-depth 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, what the intuition behind them is and which other important ideas went into your proof, such as steps for taming the arithmetic.
- You are encouraged to illustrate 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 create for the purposes of your project presentation anyhow.
- 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
- 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 will happen on Thursday May 5, 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[3]. 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.
- Talks that elide all technical details, however, also make it hard to assess the quality of the work.
- When including models and formulas on your slides, make sure they are properly typeset and crucially 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.
- Have slide count like 2/6 on every slide if you are on slide 2 out of 6.

[3] `http://symbolaris.com/course/fcps16-competition.html`

- Include a *project teaser picture* on your slide and submit this picture at aspect ratio 19:10 to be displayed at 285*150 pixels on the course web page. Be sure to respect the relevant copyright.
- Be sure to learn from Kayvon Fatahalian's advice about how to give a clear talk `https://www.cs.cmu.edu/~kayvonf/misc/cleartalktips.pdf`

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. Communicate clearly, make important points early and often, clearly state what you did, why it's relevant, etc. Practice, if possible in front of other people, so you are sure that you are communicating what you want adequately!

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

Advice on Proposal and Term Paper

1. If you use LaTeXto write your term paper, BibTeX is your friend for managing citations and references and DBLP[4] is a good source for bibliographical entries.

2. It is crucial to have a textual description of the model and its dynamics and control principles in the proposal document along with justifications for why you are modeling all its pieces like that. Without a sufficiently comprehensible description, it is hard to validate the model and tell whether you have reached the right accuracy and analyzability tradeoffs. Uncommented program model files are not effective ways of communicating what you are trying to do and why. As in the lecture notes, you should carefully develop and explain and justify the models and properties and explain the rationale behind their design. Make sure to explain and justify the differential equations, not just limit to factually stating that it is the right differential equation for the purpose. For all simplifying assumptions in your model, justify to what extent and under which circumstance they are reasonable and explain why you are making them.

3. 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. A related work discussion on verification of the International Space Station should not limit itself to a discussion of other papers having done just that. Rather, it should discuss important results where spacecrafts and models and dynamics are discussed. And papers where space and/or aircraft aspects are verified. And papers where superficially different but technically related verification steps are taken. And

[4] `http://dblp.uni-trier.de`

papers where the problem is even just identified as an important one in the first place. And any other resources you used to come up with your work. Always provide proper citations and references in related work discussions.

4. Your proposal does not have to be as detailed and perfect as the term paper. In writing your proposal, keep in mind, though, that the feedback you get can only be as good as the proposal you provide. If you fail to provide sufficient detail or do not explain it properly, feedback will have to be based on guesswork, which is not necessarily effective for you. For preliminary results and proofs, be sure to identify technical challenges and explain them in comprehensible way to enable the course staff to help you solve them.