EECE 571M / 491M: Introduction to Hybrid Systems and Control
Course Project

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1 Logistics

Students will work independently or in small groups of two or possibly three to model, analyze, and design a controller for a hybrid system. (More work will be expected from groups than individuals, and significantly more work in the groups of 3 than the groups of 2.) Students can select from a range of projects provided by the instructor, or can create their own project, in consultation with the instructor. The project will require the application (and possible extension) of hybrid system methods and tools to a specific problem. Students must justify a hybrid modeling framework, analyze the system's behavior and performance, synthesize a controller, discuss computed or analytical results, and demonstrate an understanding of potential problems in actual implementation (in measurement errors, computational complexity, or actuation). Both written and oral presentations of the project will be evaluated.

1.1 Written Component

For graduate students, a more thorough treatment is expected. As a rough guide, written reports might be approximately 5-8 pages for undergrads, 7-10 pages for graduate students – however, quality is more important than length. The written report should address the modeling, analysis, synthesis, and discussion elements indicated as above. The report should focus on application of known techniques to a specific problem. Written documents generated in Word or LaTeX are acceptable.

1.2 Oral Component

Each graduate student will give a 15 minute presentation in class. Visual aids (slides or poster) are expected. Each presentation will be followed by a brief question-and-answer period. Undergraduates may give a 10-minute presentation for extra credit.

1.3 Grading

The project will be evaluated in its written and oral components. Typical organization of the written report: abstract, introduction (including context for the work), problem formulation, method, results and discussion, conclusion and/or directions for future work. Typical organization of the oral report: introduction, existing related work, problem statement, proposed solution, results, conclusion.

Written report (75% of project grade for graduate students, 100% for undergraduate students)

Abstract (10%): succinct summary of the entire paper, as concise and coherent as possible.

Technical content (60%): accuracy, thoroughness of treatment, analytic content, appropriate citations, context with respect to other existing work, scope of the work, comprehension of relevant concepts

Literary quality (15%): spelling, grammar, clarity, style

Presentation (15%): clear and relevant figures, readable labelling, appropriate organization, neatness and professional-looking layout

Oral report (25% of project grade, required for graduate students)

Presentation (40%): readable text and figures, clean layout, organization, clarity, tailored to audience's background, handling Q&A

Technical content (60%): accuracy, placement in context with other work, scope of the work, problem formulation, method, discussion and comprehension of the results, handing Q&A

2 Cart and Pendulum Project

Consider a personalized transport vehicle such as the Segway, which is inherently unstable and requires control laws for basic operation. Segways have been proposed for use as general transport. The user stands on a small platform and grasps a handlebar at arm-height for balance. The platform is mounted on 2 wheels driven by an electric motor. The user controls the vehicle by tilting the handlebar forward or backward.

The objective of this project is to design a set of control laws, and an algorithm to switch between those control laws, such that the vehicle can smoothly accomplish a variety of maneuvers that might arise in daily operation. At the user's command, vehicle needs to be able to: 1) remain upright at rest, or 2) travel at a constant reference speed. Implicit in this is the constraint that the vehicle must also 3) accelerate and decelerate smoothly when transitioning between rest and travel, and between travel at different speeds.

One potential way of modeling the system is as an inverted pendulum on a cart, as described in `http://www.engin.umich.edu/group/ctm/examples/pend/invpen.html`. Consider the human abstracted as a rod of length l with moment of inertia I and mass m. The vehicle platform and wheels make up the cart with mass M. There is friction with coefficient b in the joint connecting the pendulum and the cart. The effect of the user tilting the handlebar is essentially to apply a force F on the cart. Hence the nonlinear equations of motion are

$$\begin{aligned} (M+m)\ddot{x} + b\dot{x} + ml\cos\theta \cdot \ddot{\theta} &= F \\ (I+ml^2)\ddot{\theta} + mgl\sin\theta + ml\cos\theta \cdot \ddot{x} &= 0 \end{aligned} \tag{1}$$

with x representing the position of the cart and θ representing the rotation of the pendulum from vertical.

Control to meet the project objectives will require two components: 1) low-level controllers to achieve each of the objectives, and 2) high-level supervisory commands such that the system as a whole meets all of the desired objectives. Hence a thorough proposal should address: 1) why a hybrid system model is appropriate for the controlled system, 2) realistic values for the model constants, 3) the inherent stability property of the uncontrolled system, 4) control design through linearization to meet each of stated control goals, separately, 5) the stability property of the controlled system, and 6) any restrictions that must be enforced to ensure stability. Regarding the low-level control synthesis in 4),

1. Friedland provides an algorithm for the synthesis of controllers to track reference trajectories $\dot{x}_r = A_r x_r$, on p. 239-240 which may be helpful, depending on your particular modeling/control strategy.

2. Dorf and Bishop (EECE 360) also provide 2-3 methods for reference tracking, depending on whether or not the system has an observer, and what the specific tracking goals are.

3. You may use whatever control method you are comfortable with (pole placement, PID, LQR, etc.) but must clearly justify your choice and discuss any potential limitations.

Lastly, the controlled hybrid system should be validated through simulation from a variety of initial conditions, and the results discussed. A Matlab file with the *uncontrolled* nonlinear system dynamics, `cartdynamics.m`, will be posted on the course website, and can be called with Matlab's integration routines, e.g.,

```
>> [t,y]=ode23('cartdynamics',[t0 tf],x0);
```

for a known time horizon $t \in [t_0, t_f]$ and known initial condition $x(t_0) = x_0$.

As with parts of the previous homeworks that were open-ended, it is fine to narrow the scope of the problem, and may even be necessary to do so at times. However, be sure to justify your assumptions and discuss their potential limitations, as well as their implications for the physical system. Expectations for the thoroughness of this work and inclusion of extensions to related problems (e.g., output-based feedback as opposed to full-state feedback, scenarios with reduced-order observability or controllability, direct control of motor as opposed to the force acting on the mass, noise in the model, etc.) will increase with the number of students working on the project.