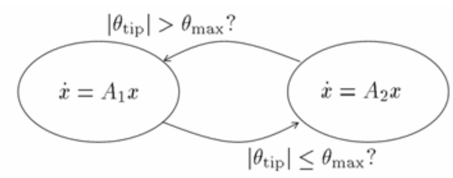
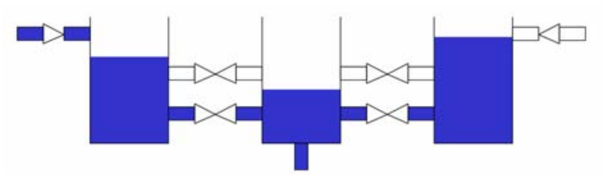
HYBRID AND SWITCHED SYSTEMS
ECE229 — WINTER 2004

Course description



As computers, digital networks, and embedded systems become ubiquitous and increasingly complex, one needs to understand the coupling between logic-based components and continuous physical systems. This prompted a shift in the standard control paradigm—in which dynamical systems were typically described by differential or difference equations—to allow the modeling, analysis, and design of systems that combine continuous dynamics with discrete logic. This new paradigm is often called *hybrid control.*

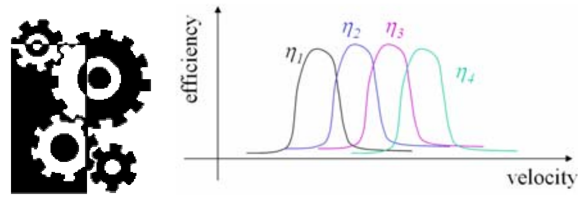


multiple-tank

This course provides an introduction to hybrid control. We start by presenting a *modeling* framework for hybrid systems that combines elements from automata theory and differential equations. The students are then guided through a set of techniques that can be used to *analyze and design* hybrid control systems. The course also includes an overview of *simulation* tools for hybrid systems with emphasis on Simulink/Stateflow, SHIFT, and Modelica.

In the last part of the course, we cover several fundamental *applications* of hybrid control. These include the control of systems that cannot be stabilized by continuous control laws and the control of systems with large uncertainty using logic-based supervisors.

transmission



The course is essentially self-contained and the students are only expected to be familiar with *linear algebra* and basic *differential equations*.

Further information (including a detailed syllabus) is available on the web at:

http://www.ece.ucsb.edu/~hespanha/ece229/

Prerequisites

Consent of instructor. This course is open to ECE, ME, ChE, and CS students.

Recommended preparation: The students should be proficient in linear algebra and basic differential equations (at the level of MATH5A-C) and some scientific programming language (e.g., MATLAB). Basic knowledge of controls concepts (at the level of ECE147A) is helpful but not essential.

Instructor

João P. Hespanha (hespanha@ece.ucsb.edu), phone: (805) 893-7042, office: Engineering I, 5157.

Office hours: Please email or phone in advance to schedule for an appointment.

This course was developed with support from the National Science Foundation.

Textbook

There is no recommended textbook for the course. Most of the material taught is covered by the following references:

[1] A. van der Schaft and H. Schumacher. *An Introduction to Hybrid Dynamical Systems*. Lecture Notes in Control and Information Sciences 251, Springer-Verlag, 2000.

[2] Daniel Liberzon. *Switching in Systems and Control*. Systems & Control: Foundations and Applications series. Birkhauser, Boston, 2003.

[3] J. Hespanha. *Encyclopedia of Life Support Systems*, Chapter Stabilization Through Hybrid Control. To appear.

[4] J. Hespanha. Tutorial on Supervisory Control. Lecture notes for the tutorial workshop "Control Using Logic and Switching" offered at the 40th Conf. on Decision and Control, Orland, FL, Dec. 2001.

Other papers and notes will also be posted in the course's webpage to complement the lectures. See References below and right-most column of the Syllabus.

Assessment format

Homeworks – 40%
Final Project – 60% (one-page project proposal is **due on Feb 5th**.)

Projects

The following two types of projects are possible in this course:

1. Solution of a research problem relevant to the student's area of research
2. Independent study of a topic not covered in class (e.g., reading a paper or book chapter).

A few project ideas:

- Regularization of Zeno systems using stochastic hybrid systems [4,17,32]
- Design of H-infinity controllers for slowly-switched systems [33]
- Survey of controllability and observability results for linear switched and hybrid systems
- Survey of recent work on networked control systems
- Survey on the use of abstractions in (hybrid) control systems.

For more project ideas, students are encouraged to look into the proceedings of the *Hybrid Systems: Computation and Control* workshop.

[A] P. Antsaklis, W. Kohn, M. Lemmon, A. Nerode, S. Sastry (Eds.): Hybrid Systems V, 1998.

[B] F.W. Vaandrager, J.H. van Schuppen (Eds.): Hybrid Systems: Computation and Control, Second International Workshop, HSCC'99, Berg en Dal, The Netherlands, March 1999.

[C] Nancy Lynch, Bruce H. Krogh (Eds.): Hybrid Systems: Computation and Control, Third International Workshop, HSCC'00, Pittsburgh, PA, USA, March 2000.

[D] M.D. Di Benedetto, A. Sangiovanni-Vincentelli (Eds.): Hybrid Systems: Computation and Control, 4th International Workshop, HSCC'01 Rome, Italy, March 28-30, 2001.

[E] C.J. Tomlin, M.R. Greenstreet (Eds.): Hybrid Systems: Computation and Control, 5th International Workshop, HSCC'02, Stanford, CA, USA, March 25-27, 2002.

[F] O. Maler and A. Pnueli (Eds.): Hybrid Systems: Computation and Control: 6th International Workshop, HSCC'03, Prague, Czech Republic, April 3-5, 2003.

Detailed Syllabus The following is a tentative schedule for the course. As revisions are needed, they will be posted on the course's web page. The rightmost column of the schedule contains the recommended reading for the topics covered on each class. Students are strongly encouraged to read these and background materials prior to the class.

Class	**Content**	**References**
Lec. #1 Jan 6	Introduction to switched control systems Examples: bouncing ball, thermostat, transmission system, inverted pendulum swing-up, multi-tank system, manufacturing systems, supervisory control.	[1,11,12,10,3] lecture notes (last changed 1/8/04)
Lec. #2 Jan 8	Formal models for hybrid systems: • Finite automata • Differential equations • Hybrid automata • Open hybrid automaton Nondeterministic vs. stochastic systems • Nondeterministic hybrid automata • Stochastic hybrid automata	[1,32] lecture notes (last changed 1/8/04)
Lec. #3 Jan 13	Trajectories of hybrid system • Solution to an hybrid system • Execution of an hybrid system Degeneracies • Finite-escape time • Chattering • Zeno trajectories • Non-continuous dependency on the initial-state	[4,17] lecture notes (last changed 1/13/04)
Lec. #4 Jan 15	Numerical simulation of hybrid automata • simulations of ODEs • zero-crossing detection Simulators • Simulink • Stateflow • SHIFT	[8,13,14,15,16] lecture notes (last changed 1/18/04)Simulink/Stateflow files (last changed 1/10/04)SHIFT files (untested) (last changed 1/10/04)Modelica files (last changed 1/18/04)
Lec. #5 Jan 20	Simulators (cont.) • Modelica Properties of hybrid automata • sequence properties (safety, liveness) • ensemble properties (stability)	[18] lecture notes (last changed 1/18/04)

Class	**Content**	**References**
Lec. #6 Jan 22	Safety/Reachability • transition systems • reachability algorithms • controller synthesis based on reachability	[19,20,22,23] lecture notes (last changed 1/24/04)
Lec. #7 Jan 27	Safety/Reachability (cont.)Lyapunov stability of ODEs • epsilon-delta and beta-function definitions • Lyapunov's stability theorem • LaSalle's invariance principle • Stability of linear systems •	[21,26] lecture notes (last changed 1/24/04)MATLAB files (last changed 1/24/04)
Lec. #8 Jan 29	Lyapunov stability of ODEs (cont.) Lyapunov stability of hybrid systems	[2,21,24,25] lecture notes (last changed 1/31/04) An alternative view (last changed 1/31/04)
Lec. #9 Feb 3	Analysis tools for hybrid systems: Impact maps • Fixed-point theorem • Stability of periodic solutions	[2,21] lecture notes (last changed 1/31/04) Mathematica file (last changed 1/31/04)
Lec. #10 Feb 5 *Project proposal due!*	Impact maps (cont.) Decoupling • Switched systems • Supervisors Lyapunov stability of switched systems	[2] lecture notes (last changed 2/8/04)
Lec. #11 Feb 10	Stability under arbitrary switching • Instability caused by switching • Common Lyapunov function • Converse results • Algebraic conditions	[2] lecture notes (last changed 2/8/04) MATLAB files (last changed 2/8/04)
Lec. #12 Feb 12	Controller realization for stable switching	[2, 27] lecture notes (last changed 2/8/04)

Class	Content	References
Lec. #13 Feb 17	Stability under slow switching • Dwell-time switching • Average dwell-time • Stability under brief instabilities Stability under state-dependent switching • State dependent common Lyapunov function • Multiple Lyapunov functions • LaSalle's invariance principle	[2,24,25,5,28] lecture notes (last changed 2/14/04)
Lec. #14 Feb 19	Computational methods to construct multiple Lyapunov functions—Linear Matrix Inequalities (LMIs) Applications: Vision-based control	[2,29] lecture notes (last changed 2/14/04)
Lec. #15 Feb 24	Applications: Supervisory control • Supervisory control architecture • Linear supervisory control	[3,30] lecture notes (last changed 2/14/04)
Lec. #16 Feb 26	Applications: Supervisory control (cont.) • Nonlinear supervisory control	[3,30] lecture notes (last changed 2/14/04)
Lec. #17 Mar 2	Modeling of network traffic	[32] lecture notes (last changed 2/29/04)
Lec. #18 Mar 4	*Student projects presentations*	
Lec. #19 Mar 9	*Student projects presentations*	
Lec. #20 Mar 11	*No class*	

References

[1] A. van der Schaft and H. Schumacher. *An Introduction to Hybrid Dynamical Systems*. Lecture Notes in Control and Information Sciences 251, Springer-Verlag, 2000.

[2] J. Hespanha. Chapter Stabilization Through Hybrid Control. In *Encyclopedia of Life Support Systems*, 2003. To appear.

[3] J. Hespanha. Tutorial on Supervisory Control. Lecture notes for the tutorial workshop "Control Using Logic and Switching" offered at the 40th Conf. on Decision and Control, Orland, FL, Dec. 2001.

[4] Jun Zhang, K. Johansson, John Lygeros, S. Sastry. Dynamical Systems Revisited: Hybrid Systems with Zeno Executions. In Nancy A. Lynch and Bruce H. Krogh (ed.). *Hybrid Systems: Computation and Control*. Springer, Mar. 2000.

[5] J. Hespanha. Uniform Stability of Switched Linear Systems: Extensions of LaSalle's Invariance Principle. To appear in the *IEEE Trans. on Automat. Contr.* Mar. 2004.

[6] J. Hespanha, A. S. Morse. Stabilization of Nonholonomic Integrators via Logic-Based Switching. *Automatica* Special Issue on Hybrid Systems, 35(3):385-393, Mar. 1999.

[7] J. Hespanha. Single-Camera Visual Servoing. In *Proc. of the 39th Conf. on Decision and Contr., 3:2533-2538*, Dec. 2000.

[8] T. Simsek. SHIFT Tutorial: A first course for SHIFT programmers. Technical report. University of California, Berkeley, Jan. 1999.

[9] S. Bohacek, J. Hespanha, J. Lee, K. Obraczka. Analysis of a TCP hybrid model. In *Proc. of the 39th Annual Allerton Conference on Communication, Control, and Computing*, Oct. 2001.

[10] A. Matveev, A. Savkin. *Qualitative Theory of Hybrid Dynamical Systems*. Control Engineering, Birkhäuser, 2000.

[11] S. Hedlund, A. Rantzer. Optimal Control of Hybrid Systems. In *Proc. of the 38th Conf. on Decision and Contr.*, Dec. 1999.

[12] K. Åström, K. Furuta. Swinging up a pendulum by energy control. *Automatica* 36:287-295, 2000.

[13] The Mathworks Inc. *Using Simulink (version 4)*, Nov. 2000.

[14] The Mathworks Inc. *Stateflow User's Guide (version 4)*, Sep. 2000.

[15] M. Otter, H. Elmqvist. Modelica: Languages, Libraries, Tools, Workshop and EU-Project RealSim. *Simulation News Europe*, pp. 3-8, Dec 200.

[16] Modelica Association. Modelica ™ — A Unified Object-Oriented Language for Physical Systems Modeling: Tutorial. Available at http://www.modelica.org/.

[17] K. Johansson, M. Egerstedt, J. Lygeros, S. Sastry. On the regularization of Zeno hybrid automata. *Syst. & Contr. Lett.*, 38:141-150, 1999.

[18] Z. Manna and A. Pnueli, *The Temporal Logic of Reactive and Concurrent Systems: specification*. Springer-Verlag, Berlin, 1992.

[19] T. Henzinger, P. Kopke, A. Puri, P. Varaiya. What's decidable about hybrid automata? *ACM Symposium on Theory of Computing*, pp. 373-383, 1995.

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[23] J. Lygeros, C. Tomlin, S. Sastry. Controllers for reachability specifications for hybrid systems. *Automatica*, 35(3):349-370, Mar. 1999.

[24] M. Branicky. Multiple Lyapunov functions and other analysis tools for switched and hybrid systems. *IEEE Trans. Automatic Control*, 43(4):475-482, April 1998.

[25] H. Ye, A. Michel, L. Hou. Stability Theory for Hybrid Dynamical Systems. *IEEE Trans. Automatic Control*, 43(4):461-474, Apr. 1998.

[26] S. Sastry. Nonlinear systems: Analysis, Stability, and Control. Springer-Verlag, New York, 1999.

[27] J. Hespanha, A. S. Morse. Switching Between Stabilizing Controllers. *Automatica*, 38(11), Nov. 2002.

[28] J. Hespanha, D. Liberzon, E. Sontag. Nonlinear observability and an invariance principle for switched systems, In *Proc. 41th Conf. on Decision and Control*, Dec. 2002.

[29] S. Boyd, L. El Ghaoui, E. Feron, V. Balakrishnan. Linear Matrix Inequalities in System and Control Theory. SIAM, 1994.

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[31] D. Liberzon, A. S. Morse, Basic problems in stability and design of switched systems. *IEEE Control Systems Magazine*, vol. 19, no. 5, pp. 59-70, Oct. 1999.

[32] S. Bohacek, J. Hespanha, J. Lee, K. Obraczka. A Hybrid Systems Modeling Framework for Fast and Accurate Simulation of Data Communication Networks. In *Proc. of the ACM Int. Conf. on Measurements and Modeling of Computer Systems (SIGMETRICS)*, June 2003.

[33] J. Hespanha. Root-Mean-Square Gains of Switched Linear Systems. *IEEE Trans. on Automat. Contr.*, 48(11), Nov. 2003.