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2 Activities and Findings

2.1 Project Activities

This is the sixth Annual Report for the NSF Large ITR on "Foundations of Hybrid and Embedded Systems and Software." This year was a no-cost extension for certain researchers at the University of California, Berkeley (Center for Hybrid and Embedded Systems and Software (CHESS), http://chess.eecs.berkeley.edu. Research at the other CHESS partners: ISIS at Vanderbilt University (Institute for Software Integrated Systems, http://www.isis.vanderbilt.edu), and the Department of Mathematical Sciences, (http://msci.memphis.edu) at the University of Memphis ended before the period covered by this report.
The web address for the overall ITR project is:

http://chess.eecs.berkeley.edu/projects/ITR/main.htm

This web site has links to the proposal and statement of work for the project.
The CHESS ITR grant has been instrumental in supporting the launch of Tomlin's new Hybrid Systems Laboratory in Cory Hall. Specifically, the grant continues to support several new directions in systems biology, centered on the development of hybrid systems models and analysis tools for the analysis and deeper understanding of several protein regulatory networks. The grant has supported Tomlin, her PhD student Anil Aswani, and a Berkeley undergraduate, Nicholas Boyd. Two additional Berkeley undergraduates, Harendra Guturu and Eugene Li, have worked on the project though have been supported by external fellowships. The research experience obtained by these undergraduates has been instrumental in helping them decide their next steps: Guturu was accepted and is currently starting the PhD program in Electrical Engineering at Stanford, and Li has been accepted into the 5th year Masters program at Berkeley and will continue working on the project this year and next. Boyd will continue working on the project as an undergraduate this year.

2.1.1 ITR Events

Main events for the ITR project in its sixth year were:

- Workshop: From Embedded Systems to Cyber-Physical Systems: a Review of the State-of-the-Art and Research Needs, April 21, 2008, St. Louis, MO

  The CPS Workshop was held in conjunction with RTAS and sponsored in part by the European Community Artist Network of Excellence and COMBEST STREP.

  The theme of the workshop was presenting an overarching view of methodologies and theories for the design of embedded and critical systems as it has emerged in the past five years and discussing the future in terms of the extension of the notion of embedded systems to Cyber-Physical Systems (CPS). In the overview of the present status of the discipline, the workshop will address heterogeneous system composition, design methods based on abstraction and refinement, interface theories, mapping of abstract entities to implementation platforms and industrial applications. The presentations will also feature industry representatives who will give their perspective of what are the gaping holes in the state of the art in their business segment and how to bridge academic accomplishments with industrial practice. The discussion about the extension of the theories and methodologies to the new generation of CPS will review the necessary steps

and a possible roadmap for research. The discussion will also include public research organizations. European Community representatives will provide the state-of-the-art and the research initiatives on embedded systems in the EU.

The program and presentations are available at
http://chess.eecs.berkeley.edu/conferences/08/StLouis/index.htm

- The Sydney-Berkeley Driving Team participated in the DARPA Grand Challenge [1] For details, see
http://chess.eecs.berkeley.edu/dgc3

- The Berkeley Electrical Engineering Annual Research Symposium (BEARS) featured an open house co-sponsored by Chess in order to display results for the benefit of our industrial partners and friends of the project. The program and presentations are available at
http://www.eecs.berkeley.edu/BEARS/2008/index.html

- A weekly Chess seminar was held at Berkeley. The speakers and topics are listed in Section 4.7.1, presentations for the seminar are available at
http://chess.eecs.berkeley.edu/seminar.htm

We organize this section by thrust areas that we established in the statement of work. As year six was a no-cost extension, we include only thrust areas funded by the no-cost extension.

2.1.2 Hybrid Systems Theory

We have proposed to build the theory of mixed discrete and continuous hybrid systems into a mathematical foundation of embedded software systems.
During the period covered by this report, Professor Henzinger's group made the following advancements:

1. New algorithms and complexity results for the verification and control of probabilistic systems (which are modeled as stochastic games). [2], [3], [4], [5]

2. New algorithms for the verification and control of real-time systems (which are modeled as timed games). [6], [7], [8], [9]

3. New algorithm for control under budget constraints. [10]

2.1.3 Deep Compositionality

Professor Henzinger's group developed CHIC, a checker for interface compatibility with applications to web services. [11], [12], [13],

2.1.4 Robust Hybrid Systems

Professor Henzinger's group developed a hierarchical coordination language for real-time tasks extended with reliability constraints (in the Giotto tradition). [14]

2.1.5 Hybrid Systems and Systems Biology

The CHESS ITR has enabled a new collaboration, between Tomlin's group and a group of developmental biologists at Lawrence Berkeley Labs and the Department of Molecular and Cell Biology at Berkeley. This group, led by Dr. Mark Biggin and Professor Mike Eisen, are studying the early Drosophila development. They have developed state of the art tools for RNA and protein data collection, and have collaborated with computer vision researchers to develop a "virtual embryo", visualizing all data at once on a 3D representation of the Drosophila embryo. We have begun a collaboration with their group to design dynamic models of this system: modeling RNA and protein concentrations to try to uncover the detailed interactions between these gene products that are key in fly development. We are developing continuous and hybrid models to represent the dynamics of this system.

Early patterning in the Drosophila melanogaster embryo occurs through a complicated network of interactions involving proteins and mRNA. One such system is the pattern of hunchback mRNA in the presence of Bicoid and Kruppel protein. This system is well-studied, but there is disagreement amongst biologists between two general models. Our aim is to provide evidence to support one of the two models in contention, and we do this through system identification methods. Our general approach is to do nonlinear regression on a parametric, nonlinear partial differential equation model which incorporates transcription, diffusion, and degradation. We perform the nonlinear regression and analyze the results of the nonlinear regression. We interpret the results in the biological context, and we also compare our results to previous work on this system.

In terms of hybrid model development, we have focused in particular on the relationship between a particular class of hybrid systems, known as piecewise affine (PWA) systems, and monotone systems (which have certain properties making them amenable to stability analysis). Monotone systems are order-preserving systems: given a partial order on any two initial conditions, the trajectories of the monotone system preserve this partial order through time. There is a rich theory of strong results about the dynamics and stability of monotone systems with continuous vector fields. These existing results do not apply to piecewise affine (PWA) systems, which have discontinuous vector fields. Though the previous work on monotone systems has largely been theoretical, there is growing interest in monotone systems due to the realization that many systems in biology are monotone. Our work considers the relationship between monotone and PWA systems, which have found applications in biology. Understanding which conditions are sufficient for a PWA system to be monotone is useful, both for understanding the dynamics as well as for designing controllers. In our work, we characterize monotonicity of PWA systems. Then, we prove analogs of the Kamke-Muller and related graph theoretical theorems, both of which provide sufficient conditions for a system with continuous vector field to be monotone. Our analogs give sufficient conditions for a PWA system to be a monotone system.

More generally, we have been studying the topology of graphs representing biological influence models, and investigating the development of a corresponding "control theory" for these graphs. The traditional control scheme has been to input a signal into a plant, where the signal is derived from either an open-loop or a closed-loop. This control strategy requires that the plant be able to accept inputs or can be modified to do so. However, this situation is not always true in biological genetic networks; in these systems, there is often no input or obvious modification to allow inputs. We believe that they require a new paradigm for control. Biotechnology techniques are such that it is easier to make topological changes to a

genetic network than it is to either change the states of the pathway or add more elements to the pathway. Thus, for such genetic networks it is important to develop a theory of control based on making large scale changes (e.g. genetic mutations) to the topology of the network; we provide steps towards such a theory. We highlight some useful results from monotone and hybrid systems theory, and show how these results can be used for such a topological control scheme. We consider the cancer-related p53 pathway as an example; we analyze this system using control theory and devise a controller.

2.2 ProjectFindings

Abstracts for key publications representing project findings during this reporting period, are provided here. A complete list of publications that appeared in print during this reporting period is given in Section 4 below, including publications representing findings that were reported in the previous annual report.

- [1]Ben Upcroft, Michael Moser, Alex Makarenko, David Johnson, Ashod Donikian, Alen Alempijevic, Robert Fitch, Will Uther, Esten Ingar Grtli, Jan Biermeyer, Humberto Gonzalez, Todd Templeton, Vason P. srini, Jonathan Sprinkle. Technical report, "DARPA Urban Challenge Technical Paper: Sydney-Berkeley Driving Team," University of Sydney; University of Technology, Sydney; University of California, Berkeley, June, 2007.

  The Sydney-Berkeley Driving Team is a collaboration between academic and research personnel from (in alphabetical order) the National Information and Communication Technology of Australia, University of California, Berkeley, University of Sydney, and the University of Technology, Sydney. This document describes the planning, actuation, simulation, communication, theoretical tasks, advancements, and projections necessary for the team to compete in the DARPA Urban Challenge. Among our major accomplishments, we claim the ability for distributed code development through the use of our component-based middleware, a high-confidence testbed which was designed and implemented from the ground up by our engineers, prototype testing in months, and robust software design and development allowing a seamless transition between simulation and online testing.

- [15]Abhijit Davare, Qi Zhu, Marco Di Natale, Claudio Pinello, Sri Kanajan, Alberto Sangiovanni-Vincentelli. "Period Optimization for Hard Real-time Distributed Automotive Systems," Design Automation Conference, 278-283, June, 2007.

  The complexity and physical distribution of modern active-safety automotive applications requires the use of distributed architectures. These architectures consist of multiple electronic control units (ECUs) connected with standardized buses. The most common configuration features periodic activation of tasks and messages coupled with run-time priority-based scheduling. The correct deployment of applications on such architectures requires end-to end latency deadlines to be met. This is challenging since deadlines must be enforced across a set of ECUs and buses, each of which supports multiple functionality. The need for accommodating legacy tasks and messages further complicates the scenario. In this work, we automatically assign task and message periods for distributed automotive systems. This is accomplished by leveraging

schedulability analysis within a convex optimization framework to simultaneously assign periods and satisfy end-to-end latency constraints. Our approach is applied to an industrial case study as well as an example taken from the literature and is shown to be both effective and efficient.

- [16]Trevor Meyerowitz. PhD thesis, "Single and Multi-CPU Performance Modeling for Embedded Systems," University of California at Berkeley, April, 2008.

  The combination of increasing design complexity, increasing concurrency, growing heterogeneity, and decreasing time to market windows has caused a crisis for embedded system developers. To deal with this problem, dedicated hardware is being replaced by a growing number of microprocessors in these systems, making software a dominant factor in design time and cost. The use of higher level models for design space exploration and early software development is critical. Much progress has been made on increasing the speed of cycle-level simulators for microprocessors, but they may still be too slow for large scale systems and are too low-level (i.e. they require a detailed implementation) for effective design space exploration. Furthermore, constructing such optimized simulators is a significant task because the particularities of the hardware must be accounted for. For this reason, these simulators are hardly flexible. This thesis focuses on modeling the performance of software executing on embedded processors in the context of a heterogeneous multi-processor system on chip in a more flexible and scalable manner than current approaches. We contend that such systems need to be modeled at a higher level of abstraction and, to ensure accuracy, the higher level must have a connection to lower-levels. First, we describe different levels of abstraction for modeling such systems and how their speed and accuracy relate. Next, the high-level modeling of both individual processing elements and also a bus-based microprocessor system are presented. Finally, an approach for automatically annotating timing information obtained from a cycle-level model back to the original application source code is developed. The annotated source code can then be simulated without the underlying architecture and still maintain good timing accuracy. These methods are driven by execution traces produced by lower level models and were developed for ARM microprocessors and MuSIC, a heterogeneous multiprocessor for Software Defined Radio from Infineon. The annotated source code executed between one to three orders of magnitude faster than equivalent cycle-level models, with good accuracy for most applications tested.

- [17]Trevor Meyerowitz, Dominik Langen, Mirko Sauermann, Alberto Sangiovanni-Vincentelli. "Source-Level Timing Annotation and Simulation for a Heterogeneous Multiprocessor," Design Automation Test Europe, IEEE, March, 2008.

  A generic and retargetable tool flow is presented that enables the export of timing data from software running on a cycle-accurate Virtual Prototype (VP) to a concurrent functional simulator. First, an annotation framework takes information gathered from running an application on the VP and automatically annotates the line-level delays back to the original source code. Then, a SystemC-based timed functional simulator runs the annotated source code much faster than the VP while preserving timing accuracy. This simulator is API-compatible with the multiprocessor's operating system. Therefore, it can compile and run unmodified applications on the host PC. This flow has been implemented for MuSIC(Multiple SIMD Cores), a heterogeneous

multiprocessor developed at Infineon to support Software Defined Radio (SDR). When compared with an optimized cycle-accurate VP of MuSIC on a variety of tests, including a multiprocessor JPEG encoder, the accuracy is within 20%, with speedups from 10x to 1000x.

- [18]Ethan Jackson. Technical report, "The Software Engineering of Domain-Specific Modeling Languages: A Survey Through Examples," Institute For Software Integrated Systems (ISIS), ISIS-07-807, March, 2008.

  This paper presents the fundamental concepts of model-based design to the broader software engineering community. We examine model-based design from the perspective of domain-specific modeling languages (DSMLs). DSMLs capture the structure, behavioral characteristics, and abstractions of complex problem domains. Model transformations defined between language syntaxes serve as high-level specifications of domain-specific compilers. Additionally, transformations are used to change abstraction levels. This paper is example driven and includes examples from a number of tools including ASML [1], Ptolemy II [2], GME [3], and GReAT [4].

- [19]Krishnendu Chatterjee, Tom Henzinger, Daniel Iercan, Christoph Kirsch, Claudio Pinello, Alberto Sangiovanni-Vincentelli. "Logical Reliability of Interacting Real-Time Tasks," Design, Automation and Test in Europe, 2008. DATE '08, 909-914, March, 2008.

  We propose the notion of logical reliability for real-time program tasks that interact through periodically updated program variables. We describe a reliability analysis that checks if the given short-term (e.g., single-period) reliability of a program variable update in an implementation is sufficient to meet the logical reliability requirement (of the program variable) in the long run. We then present a notion of design by refinement where a task can be refined by another task that writes to program variables with less logical reliability. The resulting analysis can be combined with an incremental schedulability analysis for interacting real-time tasks proposed earlier for the Hierarchical Timing Language (HTL), a coordination language for distributed real-time systems. We implemented a logical-reliability-enhanced prototype of the compiler and runtime infrastructure for HTL.

- [2]Krishnendu Chatterjee, Tom Henzinger, Koushik Sen. "Model-Checking omega-Regular Properties of Interval Markov Chains," Foundations of Software Science and Computation Structure (FoSSaCS) 2008, Roberto M. Amadio (ed.), 302-317, March, 2008.

  We study the problem of model checking Interval-valued Discrete-time Markov Chains (IDTMC). IDTMCs are discrete-time finite Markov Chains for which the exact transition probabilities are not known. Instead in IDTMCs, each transition is associated with an interval in which the actual transition probability must lie. We consider two semantic interpretations for the uncertainty in the transition probabilities of an IDTMC. In the first interpretation, we think of an IDTMC as representing a (possibly uncountable) family of (classical) discrete-time Markov Chains, where each member of the family is a Markov Chain whose transition probabilities lie within the interval range given in the IDTMC. We call this semantic interpretation Uncertain Markov Chains (UMC). In the second semantics for an IDTMC, which we call Interval Markov Decision Process

(IMDP), we view the uncertainty as being resolved through non-determinism. In other words, each time a state is visited, we adversarially pick a transition distribution that respects the interval constraints, and take a probabilistic step according to the chosen distribution. We introduce a logic omega-PCTL that can express liveness, strong fairness, and omega-regular properties (such properties cannot be expressed in PCTL). We show that the omega-PCTL model checking problem for Uncertain Markov Chain semantics is decidable in PSPACE (same as the best known upper bound for PCTL) and for Interval Markov Decision Process semantics is decidable in coNP (improving the previous known PSPACE bound for PCTL). We also show that the qualitative fragment of the logic can be solved in coNP for the UMC interpretation, and can be solved in polynomial time for a sub-class of UMCs. We also prove lower bounds for these model checking problems.We show that the model checking problem of IDTMCs with LTL formulas can be solved for both UMC and IMDP semantics by reduction to the model checking problem of IDTMC with omega-PCTL formulas.

- [20]Douglas Densmore, Trevor Meyerowitz, Abhijit Davare, Qi Zhu, Guang Yang. Technical report, "Metro II Execution Semantics for Mapping," University of California, Berkeley, UCB/EECS-2008-16, February, 2008.

  This document presents three proposals for the execution semantics of mapping in Metro II. Mapping is the relationship between what a system does (functionality) and how it does it (architecture). The main concern is whether the functionality and architecture models should execute concurrently or sequentially during simulation. Proposal #1 presents sequential execution with the functionality being executed before the architecture. Proposal #2 also presents sequential execution, but with the architecture executing before the functionality. Finally, Proposal #3 presents concurrent execution. Processes are present in the architecture to execute simultaneously with the events mapped to them in the functionality. Each of these three proposals is demonstrated on a set of design scenarios with hand traces illustrating their execution. Additionally general assumptions, glossary terms, and proposal-specific assumptions made regarding the execution semantics are discussed. Finally, the proposals are compared and contrasted, especially regarding how they can properly implement the examples and the general semantic assumptions.

- [14]Arkadeb Ghosal. PhD thesis, "A Hierarchical Coordination Language for Reliable Real-Time Tasks," EECS Department, University of California, Berkeley, January, 2008.

  Complex requirements, time-to-market pressure and regulatory constraints have made the designing of embedded systems extremely challenging. This is evident by the increase in effort and expenditure for design of safety-driven real-time control dominated applications like automotive and avionic controllers. Design processes are often challenged by lack of proper programming tools for specifying and verifying critical requirements (e.g. timing and reliability) of such applications. Platform based design, an approach for designing embedded systems, addresses the above concerns by separating requirement from architecture. The requirement specifies the intended behavior of an application while the architecture specifies the guarantees (e.g. execution speed, failure rate etc). An implementation, a mapping of the requirement on the architecture, is then analyzed for correctness. The orthogonalization of concerns makes the

specification and analyses simpler. An effective use of such design methodology has been proposed in Logical Execution Time (LET) model of real-time tasks. The model separates the timing requirements (specified by release and termination instances of a task) from the architecture guarantees (specified by worst-case execution time of the task). This dissertation proposes a coordination language, Hierarchical Timing Language (HTL), that captures the timing and reliability requirements of real-time applications. An implementation of the program on an architecture is then analyzed to check whether desired timing and reliability requirements are met or not. The core framework extends the LET model by accounting for reliability and refinement. The reliability model separates the reliability requirements of tasks from the reliability guarantees of the architecture. The requirement expresses the desired long-term reliability while the architecture provides a short-term reliability guarantee (e.g. failure rate for each iteration). The analysis checks if the short-term guarantee ensures the desired long-term reliability. The refinement model allows replacing a task by another task during program execution. Refinement preserves schedulability and reliability, i.e., if a refined task is schedulable and reliable for an implementation, then the refining task is also schedulable and reliable for the implementation. Refinement helps in concise specification without overloading analysis. The work presents the formal model, the analyses (both with and without refinement), and a compiler for HTL programs. The compiler checks composition and refinement constraints, performs schedulability and reliability analyses, and generates code for implementation of an HTL program on a virtual machine. Three real-time controllers, one each from automatic control, automotive control and avionic control, are used to illustrate the steps in modeling and analyzing HTL programs. Advisor: Alberto L. Sangiovanni-Vincentelli and Thomas A. Henzinger

- [6]Krishnendu Chatterjee, Tom Henzinger, Vinayak Prabhu. Technical report, "Trading Infinite Memory for Uniform Randomness in Timed Games," EECS Department University of California, Berkeley, UCB/EECS-2008-4, January, 2008.

  We consider concurrent two-player timed automaton games with omega-regular objectives specified as parity conditions. These games offer an appropriate model for the synthesis of real-time controllers. Earlier works on timed games focused on pure strategies for each player. We study, for the first time, the use of randomized strategies in such games. While pure (i.e., nonrandomized) strategies in timed games require infinite memory for winning even with respect to reachability objectives, we show that randomized strategies can win with finite memory with respect to all parity objectives. Also, the synthesized randomized real-time controllers are much simpler in structure than the corresponding pure controllers, and therefore easier to implement. For safety objectives we prove the existence of pure finite-memory winning strategies. Finally, while randomization helps in simplifying the strategies required for winning timed parity games, we prove that randomization does not help in winning at more states.

- [21]Alessandro Abate, Alessandro D'Innocenzo, Maria D Di Benedetto, S. Shankar Sastry. M. Egerstedt and B. Misra (eds.), "Markov Set-Chains as Abstractions of Stochastic Hybrid Systems," Springer Verlag, 2008; Chapter to appear in "Hybrid Systems: Computation and Control", 2008.

  The objective of this study is to introduce an abstraction procedure that applies to a

general class of dynamical systems, that is to discrete-time stochastic hybrid systems (dt-SHS). The procedure abstracts the original dt-SHS into a Markov set-chain (MSC) in two steps. First, a Markov chain (MC) is obtained by partitioning the hybrid state space, according to a controllable parameter, into non-overlapping domains and computing transition probabilities for these domains according to the dynamics of the dt-SHS. Second, explicit error bounds for the abstraction that depend on the above parameter are derived, and are associated to the computed transition probabilities of the MC, thus obtaining a MSC. We show that one can arbitrarily increase the accuracy of the abstraction by tuning the controllable parameter, albeit at an increase of the cardinality of the MSC. Resorting to a number of results from the MSC literature allows the analysis of the dynamics of the original dt-SHS. In the present work, the asymptotic behavior of the dt-SHS dynamics is assessed within the abstracted framework.

- [10]Krishnendu Chatterjee, Tom Henzinger, Rupak Majumdar. "Controller Synthesis with Budget Constraints," HSCC 2008, 2008.

  We study the controller synthesis problem under budget constraints. In this problem, there is a cost associated with making an observation, and a controller can make only a limited number of observations in each round so that the total cost of the observations does not exceed a given fixed budget. The controller must ensure some omega-regular requirement subject to the budget constraint. Budget constraints arise in designing and implementing controllers for resource-constrained embedded systems, where a controller may not have enough power, time, or bandwidth to obtain data from all sensors in each round. They lead to games of imperfect information, where the unknown information is not fixed a priori, but can vary from round to round, based on the choices made by the controller how to allocate its budget. We show that the budget-constrained synthesis problem for omega-regular objectives is complete for exponential time. In addition to studying synthesis under a fixed budget constraint, we study the budget optimization problem, where given a plant, an objective, and observation costs, we have to find a controller that achieves the objective with minimal average accumulated cost (or minimal peak cost). We show that this problem is reducible to a game of imperfect information where the winning objective is a conjunction of an omega-regular condition and a long-run average condition (or a least max-cost condition), and this again leads to an exponential-time algorithm. Finally, we extend our results to games over infinite state spaces, and show that the budget-constrained synthesis problem is decidable for infinite state games with stable quotients of finite index. Consequently, the discrete time budget-constrained synthesis problem is decidable for rectangular hybrid automata.

- [22]Alessandro Abate, Maria Prandini, John Lygeros, S. Shankar Sastry. M. Egerstedt and B. Misra (eds.), "Approximation of General Stochastic Hybrid Systems by Switching Diffusions with Random Hybrid Jumps," Springer Verlag, 2008; Chapter to appear in "Hybrid Systems: Computation and Control," 2008 .

  In this work we propose an approximation scheme to transform a general stochastic hybrid system (SHS) into a SHS without forced transitions due to spatial guards. Such switching mechanisms are replaced by spontaneous transitions with state-dependent transition intensities (jump rates). The resulting switching diffusion process with random hybrid jumps is shown to converge in distribution to the original stochastic hy-

brid system execution. The obtained approximation can be useful for various purposes such as, on the computational side, simulation and reachability analysis, as well as for the theoretical investigation of the model. More generally, it is suggested that SHS which are endowed exclusively with random jumping events are simpler than those that present spatial forcing transitions. In the opening of this work, the general SHS model is presented, a few of its basic properties are discussed, and the concept of generator is introduced. The second part of the paper describes the approximation procedure, introduces the new SHS model, and proves, under some assumptions, its weak convergence to the original system.

- [7]Tom Henzinger, Krishnendu Chatterjee, Vinayak Prabhu. "Timed Parity Games: Complexity and Robustness," FORMATS: Formal Modeling and Analysis of Timed Systems, 2008; To appear.

  We consider two-player games played in real time on game structures with clocks and parity objectives. The games are concurrent in that at each turn, both players independently propose a time delay and an action, and the action with the shorter delay is chosen. To prevent a player from winning by blocking time, we restrict each player to strategies that ensure that the player cannot be responsible for causing a zeno run. First, we present an efficient reduction of these games to turn-based (i.e., nonconcurrent) finite-state (i.e., untimed) parity games. The states of the resulting game are pairs of clock regions of the original game. Our reduction improves the best known complexity for solving timed parity games. Moreover, the rich class of algorithms for classical parity games can now be applied to timed parity games. Second, we consider two restricted classes of strategies for the player that represents the controller in a real-time synthesis problem, namely, limit-robust and bounded-robust strategies. Using a limit-robust strategy, the controller cannot choose an exact real-valued time delay but must allow for some nonzero jitter in each of its actions. If there is a given lower bound on the jitter, then the strategy is bounded-robust. We show that exact strategies are more powerful than limit-robust strategies, which are more powerful than bounded-robust strategies for any bound. For both kinds of robust strategies, we present efficient reductions to standard timed automaton games. These reductions provide algorithms for the synthesis of robust real-time controllers.

- [8]Krishnendu Chatterjee, Tom Henzinger, Vinayak Prabhu. "Trading Infinite Memory for Uniform Randomness in Timed Games," HSCC: Hybrid Systems – Computation and Control, 2008.

  We consider concurrent two-player timed automaton games with omega-regular objectives specified as parity conditions. These games offer an appropriate model for the synthesis of real-time controllers. Earlier works on timed games focused on pure strategies for each player. We study, for the first time, the use of randomized strategies in such games. While pure (i.e., nonrandomized) strategies in timed games require infinite memory for winning even with respect to reachability objectives, we show that randomized strategies can win with finite memory with respect to all parity objectives. Also, the synthesized randomized real-time controllers are much simpler in structure than the corresponding pure controllers, and therefore easier to implement. For safety objectives we prove the existence of pure finite-memory winning strategies. Finally, while randomization helps in simplifying the strategies required for winning timed

parity games, we prove that randomization does not help in winning at more states.

- [23]Saurabh Amin, Falk Hante, Alexandre Bayen. Technical report, "Exponential stability of switched hyperbolic systems in a bounded domain," UC Berkeley, 2008.

  We consider switching in time among a finite family of systems governed by linear hyperbolic partial differential equations on a bounded space interval. The switching system is fairly general in that the space dependent system matrix functions as well as the boundary conditions may switch in time. For the case in which the switching occurs between hyperbolic systems in the canonical diagonal form, we provide two sets of sufficient conditions for the switched system to be exponentially stable under arbitrary switching signals. These results are generalizations of the corresponding results for the un-switched case. Furthermore, we provide an explicit dwell-time bound on the switching signals that guarantee exponential stability of the switched system under the assumption that each of the individual systems are stable. Our results of stability under arbitrary switching generalize to the case in which switching occurs between non-diagonal hyperbolic systems that are diagonalizable using a common transformation. For the case in which no such transformation exists, we prove existence of a dwell-time bound on the switching signals such that exponential stability is guaranteed.

- [24]Anil Aswani, Claire Tomlin. IEEE TAC, "Monotone Piecewise Affine Systems," 2008; Submitted, to appear in 2009.

  (No abstract.)

- [25]Alessandro Abate, Maria Prandini, John Lygeros, S. Shankar Sastry. "Neuro-Dynamic Programming for Probabilistic Reachability of Stochastic Hybrid Systems," Submitted, 2008.

  (No abstract.)

- [26]Anil Aswani, Claire Tomlin. "Topology Based Control of Biological Genetic Networks," CDC, 2008; Submitted.

  The traditional controller scheme has been to input a signal into a plant, where the signal is derived from either an open-loop or a closed-loop. This control strategy requires that our plant is able to accept inputs or can be modified to do so. However, this situation is not always true in biological genetic networks; in these systems, there is often no input or obvious modification to allow inputs. Many genetic networks are different, and we believe that they require a new paradigm for control. Biotechnology techniques are such that it is easier to make topological changes to a genetic network than it is to either change the states of the pathway or add more elements to the pathway (i.e. changing the "circuit"). Thus, for such genetic networks it is important to develop a theory of control based on making large-scale changes (e.g. genetic mutations) to the topology of the network. We highlight some useful results from monotone and hybrid systems theory, and show how these results can be used for such a topological controller scheme. We consider the cancer-related, p53 pathway as an example. We analyze the system using control theory and devise a controller.

- [27]Alessandro Abate, Maria Prandini, John Lygeros, S. Shankar Sastry. Automatica, "Probabilistic Reachability and Safety for Controlled Discrete Time Stochastic Hybrid Systems," 2008; To appear.

In this work, probabilistic reachability over a finite horizon is investigated for a class of discrete time stochastic hybrid systems with control inputs. A suitable embedding of the reachability problem in a stochastic control framework reveals that it is amenable to two complementary interpretations, leading to dual algorithms for reachability computations. In particular, the set of initial conditions providing a certain probabilistic guarantee that the system will keep evolving within a desired 'safe' region of the state space is characterized in terms of a value function, and 'maximally safe' Markov policies are determined via dynamic programming. These results are of interest not only for safety analysis and design, but also for solving those regulation and stabilization problems that can be reinterpreted as safety problems. The temperature regulation problem presented in the paper as case study is one such case.

- [28]Alessandro DInnocenzo, Alessandro Abate, Maria D. Di Benedetto, S. Shankar Sastry. "Approximate Abstractions of Discrete-Time Controlled Stochastic Hybrid Systems," Submitted, 2008.

  (No abstract.)

- [29]Saurabh Amin, Falk Hante, Alexandre Bayen. Magnus Egerstedt and Bud Mishra, (eds.), "On stability of switched linear hyperbolic conservation laws with reflecting boundaries," 602-605, Hybrid Systems: Comp, Springer-Verlag, 2008.

  We consider stability of an infinite dimensional switching system, posed as a system of linear hyperbolic partial differential equations (PDEs) with reflecting boundaries, where the system parameters and the boundary conditions switch in time. Asymptotic stability of the solution for arbitrary switching is proved under commutativity of the advective velocity matrices and a joint spectral radius condition involving the boundary data.

- [11]Dirk Beyer, Arindam Chakrabarti, Krishnendu Chatterjee, Luca de Alfaro, Tom Henzinger, Marcin Jurdzinski, Freddy Mang, Cindy Song. "CHIC: Checking Interface Compatibility," UC Berkeley, November, 2007.

  CHIC is a modular verifier for behavioral compatibility checking of software and hardware components. The goal of CHIC is to be able to check that the interfaces for software or hardware components provide guarantees that satisfy the assumptions they make about each other. CHIC supports a variety of interface property specification formalisms: synchronous assume/guarantee interfaces, resource interfaces, web service interfaces, etc.

- [3]Krishnendu Chatterjee. "Stochastic Muller Games are PSPACE-complete," FSTTCS 2007: Foundations of Software Technology and Theoretical Computer Science, 436-448, December, 2007.

  The theory of graph games with omega-regular winning conditions is the foundation for modeling and synthesizing reactive processes. In the case of stochastic reactive processes, the corresponding stochastic graph games have three players, two of them (System and Environment) behaving adversarially, and the third (Uncertainty) behaving probabilistically. We consider two problems for stochastic graph games: the qualitative problem asks for the set of states from which a player can win with probability 1 (almost-sure winning); and the quantitative problem asks for the maximal

probability of winning (optimal winning) from each state. We consider omega-regular winning conditions formalized as Muller winning conditions. We present optimal memory bounds for pure (deterministic) almost-sure winning and optimal winning strategies in stochastic graph games with Muller winning conditions. We also present improved memory bounds for randomized almost-sure winning and optimal strategies. We study the complexity of stochastic Muller games and show that the quantitative analysis problem is PSPACE-complete. Our results are relevant in synthesis of stochastic reactive processes.

- [12]Arindam Chakrabarti. PhD thesis, "A Framework for Compositional Design and Analysis of Systems," UC Berkeley, December, 2007.

  Complex system design today calls for compositional design and implementation. However each component is designed with certain assumptions about the environment it is meant to operate in, and delivering certain guarantees if those assumptions are satisfied; numerous inter-component interaction errors are introduced in the manual and error-prone integration process as there is little support in design environments for machine-readably representing these assumptions and guarantees and automatically checking consistency during integration. Based on Interface Automata we propose a framework for compositional design and analysis of systems: a set of domain-specific automata-theoretic type systems for compositional system specification and analysis by behavioral specification of open systems. We focus on three different domains: component-based hardware systems communicating on bidirectional wires. concurrent distributed recursive message-passing software systems, and embedded software system components operating in resource-constrained environments. For these domains we present approaches to formally represent the assumptions and conditional guarantees between interacting open system components. Composition of such components produces new components with the appropriate assumptions and guarantees. We check satisfaction of temporal logic specifications by such components, and the substitutability of one component with another in an arbitrary context. Using this framework one can analyze large systems incrementally without needing extensive summary information to close the system at each stage. Furthermore, we focus only on the inter-component interaction behavior without dealing with the full implementation details of each component. Many of the merits of automata-theoretic model-checking are combined with the compositionality afforded by type-system based techniques. We also present an integer-based extension of the conventional boolean verification framework motivated by our interface formalism for embedded software components. Our algorithms for checking the behavioral compatibility of component interfaces are available in our tool Chic, which can be used as a plug-in for the Java IDE JBuilder and the heterogenous modeling and design environment Ptolemy II. Finally, we address the complementary problem of partitioning a large system into meaningful coherent components by analyzing the interaction patterns between its basic elements. We demonstrate the usefulness of our partitioning approach by evaluating its efficacy in improving unit-test branch coverage for a large software system implemented in C.

- [30]Saurabh Amin, Alexandre Bayen, Laurent El Ghaoui, S. Shankar Sastry. "Robust feasibility for control of water flow in a canal reservoir system," Decision and Control, 2007 46th IEEE Conference on, 1571-1577, December, 2007.

A robust control problem for distant downstream control of a reservoir-canal system modeled by Saint-Venant equations is investigated. The problem is to regulate the release of water at the upstream end such that the measured water level (or stage) at the downstream end does not deviate outside of prescribed bounds under the effect of downstream perturbations. Under the assumption of small perturbations, the Saint-Venant model is linearized around a steady state flow. The resulting linear model is discretized to obtain a linear state-space model using a method of characteristics based numerical scheme. For the state space model, the control is the upstream discharge deviation, the disturbance is the downstream discharge deviation and the output is the downstream stage deviation; the deviations are defined with respect to the steady state. The sets of admissible control, disturbance and output trajectories are modeled by polytopes. It is shown that the control problem can be formulated as a robust feasibility problem. Using linear programming duality, conditions for existence of a robustly feasible solution are derived. These conditions, being affine in the control variables, are checked using linear programming. The proposed method is applied to control a typical reservoir- canal system.

- [31]Aaron Ames, Alessandro Abate, S. Shankar Sastry. "Sufficient Conditions for the Existence of Zeno Behavior in Nonlinear Hybrid Systems via Constant Approximations," 46th IEEE Conference on Decision and Control and European Control, 4033-4038, December, 2007.

  The existence of Zeno behavior in hybrid systems is related to a certain type of equilibria, termed Zeno equilibria, that are invariant under the discrete, but not the continuous, dynamics of a hybrid system. In analogy to the standard procedure of linearizing a vector field at an equilibrium point to determine its stability, in this paper we study the local behavior of a hybrid system near a Zeno equilibrium point by considering the value of the vector field on each domain at this point, i.e., we consider constant approximations of nonlinear hybrid systems. By means of these constant approximations, we are able to derive conditions that simultaneously imply both the existence of Zeno behavior and the local exponential stability of a Zeno equilibrium point. Moreover, since these conditions are in terms of the value of the vector field on each domain at a point, they are remarkably easy to verify.

- [32]Alessandro Abate, Ashish Tiwari, S. Shankar Sastry. "The concept of Box Invariance for biologically-inspired dynamical systems," 46th IEEE Conference on Decision and Control and European Control, 5162-5167, December, 2007.

  In this paper, motivated in particular by models drawn from biology, we introduce the notion of box invariant dynamical systems. We argue that box invariance, that is, the existence of a box-shaped positively invariant region, is a characteristic of many biologically-inspired dynamical models. Box invariance is also useful for the verification of stability and safety properties of such systems. This paper presents effective characterization of this notion for some classes of systems, computational results on checking box invariance, the study of the dynamical properties it subsumes, and a comparison with related concepts in the literature. The concept is illustrated using models derived from different case studies in biology.

- [4]Krishnendu Chatterjee. "Markov Decision Processes with Multiple Long-run Average Objectives," FSTTCS 2007: Foundations of Software Technology and Theoretical

Computer Science, 473-484, December, 2007.

We consider Markov decision processes (MDPs) with multiple long-run average objectives. Such MDPs occur in design problems where one wishes to simultaneously optimize several criteria, for example, latency and power. The possible trade-offs between the different objectives are characterized by the Pareto curve. We show that every Pareto optimal point can be approximated by a memoryless strategy, for all. In contrast to the single-objective case, the memoryless strategy may require randomization. We show that the Pareto curve can be approximated (a) in polynomial time in the size of the MDP for irreducible MDPs; and (b) in polynomial space in the size of the MDP for all MDPs. Additionally, we study the problem if a given value vector is realizable by any strategy, and show that it can be decided in polynomial time for irreducible MDPs and in NP for all MDPs. These results provide algorithms for design exploration in MDP models with multiple long-run average objectives.

- [33]Alessandro Abate. PhD thesis, "Probabilistic Reachability for Stochastic Hybrid Systems: Theory, Computations, and Applications," University of California, Berkeley, November, 2007.

  Stochastic Hybrid Systems are probabilistic models suitable at describing the dynamics of variables presenting interleaved and interacting continuous and discrete components.

  Engineering systems like communication networks or automotive and air traffic control systems, financial and industrial processes like market and manufacturing models, and natural systems like biological and ecological environments exhibit compound behaviors arising from the compositions and interactions between their heterogeneous components. Hybrid Systems are mathematical models that are by definition suitable to describe such complex systems.

  The effect of the uncertainty upon the involved discrete and continuous dynamics—both endogenously and exogenously to the system—is virtually unquestionable for biological systems and often inevitable for engineering systems, and naturally leads to the employment of stochastic hybrid models.

  The first part of this dissertation introduces gradually the modeling framework and focuses on some of its features. In particular, two sequential approximation procedures are introduced, which translate a general stochastic hybrid framework into a new probabilistic model. Their convergence properties are sketched. It is argued that the obtained model is more predisposed to analysis and computations.

  The kernel of the thesis concentrates on understanding the theoretical and computational issues associated with an original notion of probabilistic reachability for controlled stochastic hybrid systems. The formal approach is based on formulating reachability analysis as a stochastic optimal control problem, which is solved via dynamic programming. A number of related and significant control problems, such as that of probabilistic safety, are reinterpreted with this approach. The technique is also computationally tested on a benchmark case study throughout the whole work. Moreover, a methodological application of the concept in the area of Systems Biology is presented: a model for the production of antibiotic as a component of the stress response network for the bacterium Bacillus subtilis is described. The model allows one to reinterpret the survival analysis for the single bacterial cell as a probabilistic safety specification problem, which is then studied by the aforementioned technique.

In conclusion, this dissertation aims at introducing a novel concept of probabilistic reachability that is both formally rigorous, computationally analyzable and of applicative interest. Furthermore, by the introduction of convergent approximation procedures, the thesis relates and positively compares the presented approach with other techniques in the literature.

Advisor: S. Shankar Sastry

- [34]Alessandro Pinto, Luca Carloni, Alberto Sangiovanni-Vincentelli. "A Communication Synthesis Infrastructure for Heterogeneous Networked Control Systems and Its Application to Building Automation and Control," EMSOFT 2007, October, 2007.

  In networked control systems the controller of a physically distributed plant is implemented as a collection of tightly interacting, concurrent processes running on a distributed execution platform. The execution platform consists of a set of heterogeneous components (sensors, actuators, and controllers) that interact through a hierarchical communication network. We propose a methodology and a framework for design exploration and automatic synthesis of the communication network. We present how our approach can be applied to the design of control systems for intelligent buildings. The input specification of the control system includes (i) the constraints on the location of its components, which are imposed by the plant, (ii) the communication requirements among the components, and (iii) an estimation of the real-time constraints for the correct behavior of the algorithms implementing the control law. The output produces an implementation of the control networks that is obtained by combining elements from a pre-defined library of communication links, protocols, interfaces, and switches. The implementation is optimal in the sense that it satisfies the given specification while minimizing an objective function that captures the overall cost of the network implementation.

- [35]A. Abate, Y. Bai, N. Sznajder, C. Talcott, A. Tiwari. "Quantitative and Probabilistic Modeling in Pathway Logic," Proceedings of the 7th IEEE International Conference on BioInformatics and BioEngineering, 922-929, October, 2007.

  This paper presents a study of possible extensions of pathway logic to represent and reason about semiquantitative and probabilistic aspects of biological processes. The underlying theme is the annotation of reaction rules with affinity information that can be used in different simulation strategies. Several such strategies were implemented, and experiments carried out to test feasibility, and to compare results of different approaches. Dimerization in the ErbB signalling network, important in cancer biology, was used as a test case.

- [5]Krishnendu Chatterjee. PhD thesis, "Stochastic Omega-Regular Games," EECS Department, University of California, Berkeley, October, 2007.

  We study games played on graphs with omega-regular conditions specified as parity, Rabin, Streett or Muller conditions. These games have applications in the verification, synthesis, modeling, testing, and compatibility checking of reactive systems. Important distinctions between graph games are as follows: (a) turn-based vs. concurrent games, depending on whether at a state of the game only a single player makes a move, or players make moves simultaneously; (b) deterministic vs. stochastic, depending on

whether the transition function is a deterministic or a probabilistic function over successor states; and (c) zero-sum vs. non-zero-sum, depending on whether the objectives of the players are strictly conflicting or not. We establish that the decision problem for turn-based stochastic zero-sum games with Rabin, Streett, and Muller objectives are NP-complete, coNP-complete, and PSPACE-complete, respectively, substantially improving the previously known 3EXPTIME bound. We also present strategy improvement style algorithms for turn-based stochastic Rabin and Streett games. In the case of concurrent stochastic zero-sum games with parity objectives we obtain a PSPACE bound, again improving the previously known 3EXPTIME bound. As a consequence, concurrent stochastic zero-sum games with Rabin, Streett, and Muller objectives can be solved in EXPSPACE, improving the previously known 4EXPTIME bound. We also present an elementary and combinatorial proof of the existence of memoryless epsilon-optimal strategies in concurrent stochastic games with reachability objectives, for all real epsilon¿0, where an epsilon-optimal strategy achieves the value of the game with in epsilon against all strategies of the opponent. We also use the proof techniques to present a strategy improvement style algorithm for concurrent stochastic reachability games. We then go beyond omega-regular objectives and study the complexity of an important class of quantitative objectives, namely, limit-average objectives. In the case of limit-average games, the states of the graph is labeled with rewards and the goal is to maximize the long-run average of the rewards. We show that concurrent stochastic zero-sum games with limit-average objectives can be solved in EXPTIME. Finally, we introduce a new notion of equilibrium, called secure equilibrium, in non-zero-sum games which captures the notion of conditional competitiveness. We prove the existence of unique maximal secure equilibrium payoff profiles in turn-based deterministic games, and present algorithms to compute such payoff profiles. We also show how the notion of secure equilibrium extends the assume-guarantee style of reasoning in the game theoretic framework.

- [36]Alessandro Abate, Maria Prandini, John Lygeros, S. Shankar Sastry. "Probabilistic Safety and Optimal Control for Survival Analysis of Bacillus Subtilis," Proceedings of the 2nd Conference on Foundations of Systems Biology in Engineering, 527-532, September, 2007.

  The investigation of the stress response network of Bacillus Subtilis ATCC 6633 offers a detailed explanation of how the bacterium reacts to competitive environmental conditions, among the many options, by producing the antibiotic subtilin in order to directly suppress other cells while getting immunized. The mechanisms of this generation are fairly well understood and described by a genetic and protein pathway that involves some non-deterministic interplay between the involved quantities: in particular, the presence of switching modes exhibits the activation/deactivation of certain genes and the production of proteins; these transitions in turn depend non-linearly on the above quantities.

  According to the general principles of evolution, we may postulate that the way this pathway functions is according to certain criteria and levels of optimality; in this context optimality is intended as a measure of personal fitness or, in the particular instance, of own survival. In particular, one would expect that the switches in the network happen 'optimally' in the above sense.

  In this work, we look at a recently developed dynamical model for the genetic network

describing the production of subtilin and propose modifications for the model to bring it in line with other evidence reported in the literature. We obtain a system that presents partially decoupled high-level dynamics (those dealing with the population size and the nutrient level) and low-level ones (those describing the mechanism of generation of subtilin by the single cell). The high-level model is non-linear and deterministic, while the low-level one is piecewise-affine, hybrid and stochastic.

The new model allows one to reinterpret the survival analysis for the single B. subtilis cell and study it as a probabilistic, decentralized safety specification problem over a short time horizon; it is 'probabilistic' because of the certainly stochastic dynamics, as well as according to possible 'trembling' features of the actions; it is 'over a short time horizon' because of the greedy nature of the survival games that are played at this level; it is naturally 'decentralized' because each entity, while optimizing for its own fitness (which depends on global information), does not communicate with the competitors, nor has knowledge of their actions; furthermore, we motivate that the solution of the problem may not be globally optimal.

Using recently developed techniques for probabilistic verification in a stochastic hybrid systems setting, we reinterpret the above probabilistic safety problem as a (stochastic) optimal control one, where the controls are (possibly randomized) functions of the state-space that encode the switches in the network. Finally, the solution of this short-time-horizon, stochastic and decentralized optimal control problem yields the structure of the switching behaviors under study. Matching these outcomes with the data in the literature allows concluding that the corresponding mechanisms in the subtilin production network function with a degree of optimality, according to certain survival criteria.

- [9]Thomas Brihaye, Tom Henzinger, Vinayak Prabhu, Jean-Franois Raskin. "Minimum-time reachability in timed games," ICALP 2007 Automata, Languages and Programming, 825-837, July, 2007.

  We consider the minimum-time reachability problem in concurrent two-player timed automaton game structures. We show how to compute the minimum time needed by a player to reach a target location against all possible choices of the opponent.We do not put any syntactic restriction on the game structure, nor do we require any player to guarantee time divergence.We only require players to use receptive strategies which do not block time. The minimal time is computed in part using a fixpoint expression, which we show can be evaluated on equivalence classes of a non-trivial extension of the clock-region equivalence relation for timed automata.

- [13]Dirk Beyer, Arindam Chakrabarti, Tom Henzinger, Sanjit A. Seshia. "An Application of Web-Service Interfaces," IEEE International Conference on Web Services (ICWS) 2007, IEEE Computer Society Press, 831-838, July, 2007.

  We present a case study to illustrate our formalism for the specification and verification of the method-invocation behavior of web-service applications constructed from asynchronously interacting multi-threaded distributed components. Our model is expressive enough to allow the representation of recursion and dynamic thread creation, and yet permits the algorithmic analysis of the following two questions: (1) Does a given service satisfy a safety specification? (2)Can a given service be substituted by a

another service in an arbitrary context? Our case study is based on the Amazon.com E-Commerce Services (ECS) platform.

- [37]Jeff Gray, Juha-Pekka Tolvanen, Steven Kelly, Anirudda Gokhale, Sandeep Neema, Jonathan Sprinkle. Paul A. Fishwick (ed.), "Domain-Specific Modeling (in CRC Handbook of Dynamic System Modeling)," 7, (in publication), CRC Press, 2007.

  Since the inception of the software industry, modeling tools have been a core product offered by commercial vendors. In this chapter, the essential characteristics of DSM are presented, including a discussion regarding those domains that are most likely to benefit from DSM adoption. The chapter also contains a case study section where two different examples are presented in two different metamodeling tools. An overview of the history of metamodeling tools is also provided, as well as concluding comments.

- [38]A. Abate S. Amin and M. Prandini and J. Lygeros and S. Sastry. A. Bemporad A. Bicchi and G. Buttazzo (eds.), "Computational Approaches to Reachability Analysis of Stochastic Hybrid Systems," 4-17, 4416, Springer Verlag, 2007.

  This work investigates some of the computational issues involved in the solution of probabilistic reachability problems for discretetime, controlled stochastic hybrid systems. It is first argued that, under rather weak continuity assumptions on the stochastic kernels that characterize the dynamics of the system, the numerical solution of a discretized version of the probabilistic reachability problem is guaranteed to converge to the optimal one, as the discretization level decreases. With reference to a benchmark problem, it is then discussed how some of the structural properties of the hybrid system under study can be exploited to solve the probabilistic reachability problem more efficiently. Possible techniques that can increase the scale-up potential of the proposed numerical approximation scheme are suggested.

- [39]A. Abate, A. D'Innocenzo, G. Pola, M. D. Di Benedetto, S. S. Sastry. A. Bemporad and A. Bicchi and G. Buttazzo (eds.), "The Concept of Deadlock and Livelock in Hybrid Control Systems," 628-632, 4416, Springer Verlag, 2007.

  This short paper qualitatively introduces the definition of the concepts of Deadlock and Livelock for a general class of Hybrid Control Systems (HCS). Such a characterization hinges on three important aspects: firstly, the concept of composition of HCS; secondly, the general concept of specifications and their composition for HCS; finally, the dynamical structure and behaviors of HCS. The first aspect is introduced in a novel manner, including ideas from the literature of discrete transition systems and accounting for concepts such as that of dynamical feedback interconnection. The second point includes general properties that are of interest from a systems and control theory perspective. The third part categorizes the diverse and possibly pathological behaviors that are distinctive of HCS. A first look at the problem of Deadlock and Livelock Verification concludes the manuscript.

- [40]Aaron Ames. Michael Farber, R . Ghrist, M. Burger, D . Koditschek (eds.), "Homotopy Meaningful Hybrid Model Structures," 121-144, American Mathematical Society, 2007.

  Hybrid systems are systems that display both discrete and continuous behavior and, therefore, have the ability to model a wide range of robotic systems such as those

undergoing impacts. The main observation of this paper is that systems of this form relate in a natural manner to very special diagrams over a category, termed hybrid objects. Using the theory of model categories, which provides a method for "doing homotopy theory" on general categories satisfying certain axioms, we are able to understand the homotopy theoretic properties of such hybrid objects in terms of their "non-hybrid" counterparts. Specifically, given a model category, we obtain a "homotopy meaningful" model structure on the category of hybrid objects over this category with the same discrete structure, i.e., a model structure that relates to the original non-hybrid model structure by means of homotopy colimits, which necessarily exist. This paper, therefore, lays the groundwork for "hybrid homotopy theory."

3 Outreach

3.1 Project Training and Development

We continue to use the CHESS Software Lab, which is focused on supporting the creation of publication-quality software in support of embedded systems design. The lab is a room with wireless and wired network connections, a large table for collaborative work, a large format printer (used for UML diagrams and poster preparation), comfortable furniture supporting extended hours of collaborative work, a coffee machine, and a library that inherited a collection of software technology books from the Ptolemy Project. This room is used to promote a local version of the Extreme Programming (XP) software design practice, which advocates pair programming, design reviews, code reviews, extensive use of automated regression tests, and a collaboratively maintained body of code (we use CVS). The room began operation in March of 2003 and has been in nearly constant use for collaborative design work. The principal focus of that work has been on advanced tool architectures for hybrid and embedded software systems design.

3.2 Outreach Activities

Continuing in our mission to build a modern systems science (MSS) with profound implications on the nature and scope of computer science and engineering research, the structure of computer science and electrical engineering curricula, and future industrial practice. This new systems science must pervade engineering education throughout the undergraduate and graduate levels. Embedded software and systems represent a major departure from the current, separated structure of computer science (CS), computer engineering (CE), and electrical engineering (EE). In fact, the new, emerging systems science reintegrates information and physical sciences. The impact of this change on teaching is profound, and cannot be confined to graduate level.
This year we have continued our work to lay the foundation for a new philosophy of undergraduate teaching at the participating institutions.

3.2.1 Curriculum Development for Modern Systems Science (MSS)

Our agenda is to restructure computer science and electrical engineering curricula to adapt to a tighter integration of computational and physical systems. Embedded software and systems represent a major departure from the current, separated structure of computer

science (CS), computer engineering (CE), and electrical engineering (EE). In fact, the new, emerging systems science reintegrates information and physical sciences. The impact of this change on teaching is profound, and cannot be confined to graduate level. Based on the ongoing, groundbreaking effort at UCB, we are engaged in retooling undergraduate teaching at the participating institutions, and making the results widely available to encourage critical discussion and facilitate adoption.

We are engaged in an effort at UCB to restructure the undergraduate systems curriculum (which includes courses in signals and systems, communications, signal processing, control systems, image processing, and random processes). The traditional curriculum in these areas is mature and established, so making changes is challenging. We are at the stage of attempting to build faculty consensus for an approach that shortens the pre-requisite chain and allows for introduction of new courses in hybrid systems and embedded software systems.

3.2.2 Undergrad Course Insertion and Transfer

At many institutions, introductory courses are quite large. This makes conducting such a course a substantial undertaking. In particular, the newness of the subject means that there are relatively few available homework and lab exercises and exam questions. To facilitate use of this approach by other instructors, we have engaged technical staff to build web infrastructure supporting such courses. We have built an instructor forum that enables submission and selection of problems from the text and from a library of submitted problems and exercises. A server-side infrastructure generates PDF files for problem sets and solution sets.

The tight integration of computational and physical topics offers opportunities for leveraging technology to illustrate fundamental concepts. We have developed a suite of web pages with applets that use sound, images, and graphs interactively. Our staff has extended and upgraded these applets and created a suite of PowerPoint slides for use by instructors.

We have begun to define an upper division course in embedded software (aimed at juniors and seniors). This new course will replace the control course at the upper division level at San Jose State. We also continued to teach at UC Berkeley the integrated course designed by Prof. Lee, which employs techniques discovered in the hybrid and embedded systems research to interpret traditional signals.

Course: Introduction to Embedded Systems (UCB EECS 124)
http://chess.eecs.berkeley.edu/eecs124/

Instructors:
Prof. Edward A. Lee
Prof. Sanjit A. Seshia
Prof. Claire J. Tomlin

EECS 124 is a new course, being offered on a pilot basis in Spring 2008, intended to introduce students to the design and analysis of computational systems that interact with physical processes. Applications of such systems include medical devices and systems, consumer electronics, toys and games, assisted living, traffic control and safety, automotive systems, process control, energy management and conservation, environmental control, aircraft control systems, communications systems, instrumentation, critical infrastructure control (electric power, water resources, and communications systems for example), robotics and distributed robotics (telepresence, telemedicine), defense systems, manufacturing, and smart structures.

A major theme of this course will be on the interplay of practical design with formal models of systems, including both software components and physical dynamics. A major emphasis will be on building high confidence systems with real-time and concurrent behaviors.

Course: Introduction to Control Design Techniques (UCB EECS 128)
http://inst.eecs.berkeley.edu/ ee128/fa08//
Instructor:
Prof. Claire J. Tomlin

In 2008, Professor Tomlin has redesigned the undergraduate control theory and engineering course, EECS 128, adding new labs and course material. The new material will be taught in the Fall Semester of 2008.
The abstract for the class is below:
Root-locus and frequency response techniques for control system synthesis. State-space techniques for modeling, full-state feedback regulator design, pole placement, and observer design. Combined observer and regulator design. Lab experiments on computers connected to mechanical systems.

- Transfer function and state space models for control system analysis and synthesis. Pole locations and relationship to time response. Root locus methods. Stability.
- Feedback. Review of single-input single output (SISO) analysis and control methods in the frequency domain (Bode, Nyquist).
- SISO analysis and control using state space models. The matrix exponential and its relationship to time response. Controllability and observability. Combining state feedback with observers.
- Multi-input multi-output analysis and control using state space models.
- The linear quadratic regulator.

3.2.3 Graduate Courses

As part of the no-cost extension, a course in embedded systems was taught in the area of embedded and hybrid systems, as well as systems modeling. This course is a reflection of the teaching and curriculum goals of the ITR and its affiliated faculty.

Course: Linear System Theory(UCB EE221A)
http://inst.eecs.berkeley.edu/ ee221A/fa08//
Instructor: Claire J. Tomlin

Professor Tomlin modernizing the graduate course in linear system theory, EECS 221A, adding units in linear programming and more general optimization. The new material will be taught in the Fall Semester of 2008.
The abstract for the class is below:
This course provides a comprehensive introduction to the modeling, analysis, and control of linear dynamical systems. Topics include: A review of linear algebra and matrix theory. The solutions of linear equations. Least-squares approximation and linear programming. Linear ordinary differential equations: existence and uniqueness of solutions, the state-transition matrix and matrix exponential. Input-output and

internal stability; the method of Lyapunov. Controllability and observability; basic realization theory. Control and observer design: pole placement, state estimation. Linear quadratic optimal control: Riccati equation and properties of the LQ regulator. Advanced topics such as robust control and hybrid system theory will be presented based on allowable time and interest from the class.
This course provides a solid foundation for students doing research that requires the design and use of dynamic models. Students in control, circuits, signal processing, communications and networking are encouraged to take this course.

- Linear Algebra: Fields, vector spaces, subspaces, bases, dimension, range and Null spaces, linear operators, norms, inner products, adjoints.
- Matrix Theory: Eigenspaces, Jordan form, Hermitian forms, positive definiteness, singular value decomposition, functions of matrices, spectral mapping theorem, computational aspects.
- Optimization: Linear equations, least-squares approximation, linear programming.
- Differential Equations: existence and uniqueness of solutions, Lipschitz continuity, linear ordinary differential equations, the notion of state, the state-transition matrix.
- Stability: Internal stability, input-output stability, the method of Lyapunov.
- Linear Systems - open-loop aspects: controllability and observability, duality, canonical forms, the Kalman decomposition, realization theory, minimal realizations.
- Linear systems - feedback aspects: pole placement, stabilizability and detectability, observers, state estimation, the separation principle.
- Linear quadratic optimal control: least-squares control and estimation, Riccati equations, properties of the LQ regulator.
- Advanced topics: robust control, hybrid systems.

Course: Embedded System Design: Models, Validation, and Synthesis (UCB EE249)
http://inst.eecs.berkeley.edu/ ee249/fa07/
Instructor: Prof. Alberto Sangiovanni-Vincentelli

Embedded systems are electronics systems that sense physical quantities, elaborate the data and respond to the environment by sending commands to actuators. These computing systems are everywhere: in our homes, automobiles, and work place. Their complexity increases steadily: a top-of-the-line car electrical system may include more than 80 processors that control its power train (engine and transmission) as well as its stability (suspension and chassis), interior functionality (air conditioning, displays), stability, communication (cellular) and entertainment; the comfort and security of a modern building requires the installation of thousands of sensors reporting measurements to central computers that run sophisticated control algorithms for energy-use

optimization and safety functions. New methods are needed to allow designing reliable and secure distributed systems quickly, inexpensively and, most importantly, with no errors to avoid recalls and expensive retrofits. We argue that a novel system theory is needed that at the same time is computational and physical, bringing together the traditional computer science abstraction, where the physical world has been carefully and artfully hidden, and classical system theory that deals with the physical foundations of engineering where quantities such as time, power and geometric dimensions play a fundamental role in the models upon which this theory is based. The basis of this theory cannot be but a set of novel abstractions that partially expose the physical reality to the higher levels and methods to manipulate the abstractions and link them in a coherent whole.
This class presents approaches to the new system science based on theories, methods and tools that were in part developed at the Berkeley Center for Hybrid and Embedded Software Systems (CHESS) and the Giga-scale System Research Center (GSRC) where heterogeneity, concurrency, multiple levels of abstraction play an important role and where a set of correct-by-construction refinement techniques are introduced as a way of reducing substantially design time and errors. Real-life applications including car electronics and building automation are used to illustrate system-level design methodologies and tools.

4 Publications and Products

In this section, we list published papers only. Submitted papers and in press papers are described in Section 2.2.

4.1 Technical reports

- [1]Ben Upcroft, Michael Moser, Alex Makarenko, David Johnson, Ashod Donikian, Alen Alempijevic, Robert Fitch, Will Uther, Esten Ingar Grtli, Jan Biermeyer, Humberto Gonzalez, Todd Templeton, Vason P. srini, Jonathan Sprinkle. Technical report, "DARPA Urban Challenge Technical Paper: Sydney-Berkeley Driving Team," University of Sydney; University of Technology, Sydney; University of California, Berkeley, June, 2007.

- [18]Ethan Jackson. Technical report, "The Software Engineering of Domain-Specific Modeling Languages: A Survey Through Examples," Institute For Software Integrated Systems (ISIS), ISIS-07-807, March, 2008.

- [20]Douglas Densmore, Trevor Meyerowitz, Abhijit Davare, Qi Zhu, Guang Yang. Technical report, "Metro II Execution Semantics for Mapping," University of California, Berkeley, UCB/EECS-2008-16, February, 2008.

- [6]Krishnendu Chatterjee, Tom Henzinger, Vinayak Prabhu. Technical report, "Trading Infinite Memory for Uniform Randomness in Timed Games," EECS Department University of California, Berkeley, UCB/EECS-2008-4, January, 2008.

- [23]Saurabh Amin, Falk Hante, Alexandre Bayen. Technical report, "Exponential stability of switched hyperbolic systems in a bounded domain," UC Berkeley, 2008.

4.2 Software

- [11]Dirk Beyer, Arindam Chakrabarti, Krishnendu Chatterjee, Luca de Alfaro, Tom Henzinger, Marcin Jurdzinski, Freddy Mang, Cindy Song. "CHIC: Checking Interface Compatibility," UC Berkeley, November, 2007.

4.3 PhD theses

- [16]Trevor Meyerowitz. PhD thesis, "Single and Multi-CPU Performance Modeling for Embedded Systems," University of California at Berkeley, April, 2008.
- [14]Arkadeb Ghosal. PhD thesis, "A Hierarchical Coordination Language for Reliable Real-Time Tasks," EECS Department, University of California, Berkeley, January, 2008.
- [12]Arindam Chakrabarti. PhD thesis, "A Framework for Compositional Design and Analysis of Systems," UC Berkeley, December, 2007.
- [33]Alessandro Abate. PhD thesis, "Probabilistic Reachability for Stochastic Hybrid Systems: Theory, Computations, and Applications," University of California, Berkeley, November, 2007.
- [5]Krishnendu Chatterjee. PhD thesis, "Stochastic Omega-Regular Games," EECS Department, University of California, Berkeley, October, 2007.
- [41]Daniel Lazaro Cuadrado. PhD thesis, "Automated Distribution Simulation in Ptolemy II," Aalborg University, April, 2008.

4.4 Conference papers

- [17]Trevor Meyerowitz, Dominik Langen, Mirko Sauermann, Alberto Sangiovanni-Vincentelli. "Source-Level Timing Annotation and Simulation for a Heterogeneous Multiprocessor," Design Automation Test Europe, IEEE, March, 2008.
- [19]Krishnendu Chatterjee, Tom Henzinger, Daniel Iercan, Christoph Kirsch, Claudio Pinello, Alberto Sangiovanni-Vincentelli. "Logical Reliability of Interacting Real-Time Tasks," Design, Automation and Test in Europe, 2008. DATE '08, 909-914, March, 2008.
- [2]Krishnendu Chatterjee, Tom Henzinger, Koushik Sen. "Model-Checking omega-Regular Properties of Interval Markov Chains," Foundations of Software Science and Computation Structure (FoSSaCS) 2008, Roberto M. Amadio (ed.), 302-317, March, 2008.
- [10]Krishnendu Chatterjee, Tom Henzinger, Rupak Majumdar. "Controller Synthesis with Budget Constraints," HSCC 2008, 2008.
- [32]Alessandro Abate, Ashish Tiwari, S. Shankar Sastry. "The concept of Box Invariance for biologically-inspired dynamical systems," 46th IEEE Conference on Decision and Control and European Control, 5162-5167, December, 2007.

- [30]Saurabh Amin, Alexandre Bayen, Laurent El Ghaoui, S. Shankar Sastry. "Robust feasibility for control of water flow in a canal reservoir system," Decision and Control, 2007 46th IEEE Conference on, 1571-1577, December, 2007.

- [35]A. Abate, Y. Bai, N. Sznajder, C. Talcott, A. Tiwari. "Quantitative and Probabilistic Modeling in Pathway Logic," Proceedings of the 7th IEEE International Conference on BioInformatics and BioEngineering, 922-929, October, 2007.

- [36]Alessandro Abate, Maria Prandini, John Lygeros, S. Shankar Sastry. "Probabilistic Safety and Optimal Control for Survival Analysis of Bacillus Subtilis," Proceedings of the 2nd Conference on Foundations of Systems Biology in Engineering, 527-532, September, 2007.

- [4]Krishnendu Chatterjee. "Markov Decision Processes with Multiple Long-run Average Objectives," FSTTCS 2007: Foundations of Software Technology and Theoretical Computer Science, 473-484, December, 2007.

- [3]Krishnendu Chatterjee. "Stochastic Muller Games are PSPACE-complete," FSTTCS 2007: Foundations of Software Technology and Theoretical Computer Science, 436-448, December, 2007.

- [8]Krishnendu Chatterjee, Tom Henzinger, Vinayak Prabhu. "Trading Infinite Memory for Uniform Randomness in Timed Games," HSCC: Hybrid Systems – Computation and Control, 2008.

- [7]Tom Henzinger, Krishnendu Chatterjee, Vinayak Prabhu. "Timed Parity Games: Complexity and Robustness," FORMATS: Formal Modeling and Analysis of Timed Systems, 2008; To appear.

- [31]Aaron Ames, Alessandro Abate, S. Shankar Sastry. "Sufficient Conditions for the Existence of Zeno Behavior in Nonlinear Hybrid Systems via Constant Approximations," 46th IEEE Conference on Decision and Control and European Control, 4033-4038, December, 2007.

- [9]Thomas Brihaye, Tom Henzinger, Vinayak Prabhu, Jean-Franois Raskin. "Minimum-time reachability in timed games," ICALP 2007 Automata, Languages and Programming, 825-837, July, 2007.

- [34]Alessandro Pinto, Luca Carloni, Alberto Sangiovanni-Vincentelli. "A Communication Synthesis Infrastructure for Heterogeneous Networked Control Systems and Its Application to Building Automation and Control," EMSOFT 2007, October, 2007.

- [13]Dirk Beyer, Arindam Chakrabarti, Tom Henzinger, Sanjit A. Seshia. "An Application of Web-Service Interfaces," IEEE International Conference on Web Services (ICWS) 2007, IEEE Computer Society Press, 831-838, July, 2007.

- [15]Abhijit Davare, Qi Zhu, Marco Di Natale, Claudio Pinello, Sri Kanajan, Alberto Sangiovanni-Vincentelli. "Period Optimization for Hard Real-time Distributed Automotive Systems," Design Automation Conference, 278-283, June, 2007.

4.5 Book chapters or sections

- [39]A. Abate, A. D'Innocenzo, G. Pola, M. D. Di Benedetto, S. S. Sastry. A. Bemporad and A. Bicchi and G. Buttazzo (eds.), "The Concept of Deadlock and Livelock in Hybrid Control Systems," 628-632, 4416, Springer Verlag, 2007.

- [38]A. Abate S. Amin and M. Prandini and J. Lygeros and S. Sastry. A. Bemporad A. Bicchi and G. Buttazzo (eds.), "Computational Approaches to Reachability Analysis of Stochastic Hybrid Systems," 4-17, 4416, Springer Verlag, 2007.

- [40]Aaron Ames. Michael Farber, R . Ghrist, M. Burger, D . Koditschek (eds.), "Homotopy Meaningful Hybrid Model Structures," 121-144, American Mathematical Society, 2007.

- [37]Jeff Gray, Juha-Pekka Tolvanen, Steven Kelly, Anirudda Gokhale, Sandeep Neema, Jonathan Sprinkle. Paul A. Fishwick (ed.), "Domain-Specific Modeling (in CRC Handbook of Dynamic System Modeling)," 7, (in publication), CRC Press, 2007.

- [22]Alessandro Abate, Maria Prandini, John Lygeros, S. Shankar Sastry. M. Egerstedt and B. Misra (eds.), "Approximation of General Stochastic Hybrid Systems by Switching Diffusions with Random Hybrid Jumps," Springer Verlag, 2008; Chapter to appear in "Hybrid Systems: Computation and Control," 2008 .

- [21]Alessandro Abate, Alessandro D'Innocenzo, Maria D Di Benedetto, S. Shankar Sastry. M. Egerstedt and B. Misra (eds.), "Markov Set-Chains as Abstractions of Stochastic Hybrid Systems," Springer Verlag, 2008; Chapter to appear in "Hybrid Systems: Computation and Control", 2008.

- [29]Saurabh Amin, Falk Hante, Alexandre Bayen. Magnus Egerstedt and Bud Mishra, (eds.), "On stability of switched linear hyperbolic conservation laws with reflecting boundaries," 602-605, Hybrid Systems: Comp, Springer-Verlag, 2008.

4.6 Journal articles

- [27]Alessandro Abate, Maria Prandini, John Lygeros, S. Shankar Sastry. Automatica, "Probabilistic Reachability and Safety for Controlled Discrete Time Stochastic Hybrid Systems," 2008; To appear.

4.7 Dissemination

Although this is a long term project focused on foundations, we are actively working to set up effective technology transfer mechanisms for dissemination of the research results. A major part of this is expected to occur through the open dissemination of software tools.

4.7.1 The 2007-2008 Chess seminar series

The Chess seminar series provides a weekly forum for the problems and solutions found and solved by Chess members, as well as ongoing research updates. This forum works best when the audience is diverse in background, because the goal is to aid researchers in seeing how

the other sub-disciplines are approaching similar problems, or to encourage them to work on problems they had not yet considered.
A full listing of this project-year's speakers is below. Most talks can be downloaded from the seminar website, at http://chess.eecs.berkeley.edu/seminar.htm

- "Formal Specification and Analysis of Real-Time Systems in Real-Time Maude"
  Peter Csaba Olveczky, University of Oslo, May 13, 2008
- "Partial Evaluation for Optimized Compilation of Actor-Oriented Models"
  Gang Zhou, Monday, May 12, 2008, 3:30-4:30
- "Specification and Analysis of Electronic Contracts"
  Gerardo Schneider, University of Oslo, May 6, 2008
- "Anytime Control Algorithms for Embedded Real-Time Systems"
  Luca Greco, University of Salerno, April 29, 2008
- "When can a UAV get smart with its operator, and say 'NO!'?"
  Prof. Jonathan Sprinkle, University of Arizona, April 15, 2008
- "Model-Based Design of a Power Window System: Modeling, Simulation, and Validation"
  Pieter J. Mosterman, The MathWorks, April 8, 2008.
- "From Automated Software Testing to Likely Program Invariant Generation"
  Koushik Sen, UC Berkeley, March 18, 2008.
- "Numerical solution of nonlinear differential equations in musical synthesis"
  David Yeh, Stanford, March 11, 2008.
- "Single and Multi-CPU Performance Modeling for Embedded Systems"
  Trevor Meyerowitz, UC Berkeley, February 26, 2008.
- "Model-Based Development of Fault-Tolerant Real-Time Systems"
  Prof. Alois Knoll, Technical University of Munich, February 19, 2008.
- "Enhancing the Visual Experience on the Mobile Computing and Communications Platforms"
  Achin Bhowmik, Intel Corporation, February 12, 2008.
- "Inventing and Prototyping Social Devices
  Michael Winter, Stupid Fun Club, February 5, 2008.
- "A Hierarchical Coordination Language for Reliable Real-Time Tasks"
  Arkadeb Ghosal, UC Berkeley, January 22, 2008.
- "Algorithms for an Autonomous Car"
  Edwin Olson, MIT CSAIL, January 8, 2008.
- "Reducing Energy consumption in Wireless Sensor Networks"
  Carlo Fischione, UC Berkeley, December 11, 2007.

- "From Specifications to Systems"
  Orna Kupferman, Hebrew University, December 4, 2007.

- "Communication Synthesis with Applications to On-Chip Communication and Building Automation Systems"
  Alessandro Pinto, UC Berkeley, November 27, 2007.

- "The Theory of Fast and Robust Adaptation"
  Naira Hovakimyan, Virginia Tech, November 13, 2007.

- "Using the Principles of Synchronous Languages in Discrete-event and Continuous-time Models"
  Edward Lee, UC Berkeley, October 23, 2007.

- "Design of Robust Dynamic Networks"
  Andrzej Banaszuk, United Technologies, October 16, 2007.

- "From Actors to Gates"
  Jorn Janneck, Xilinx Research Labs, October 9, 2007.

- "Ingredients for Successful System Level Automation & Design Methodology - Support for Multiple Models of Computation, Directed test case generation, Reflection & Introspection and Service-oriented tool integration environment"
  Hiren Patel, UC Berkeley, October 4, 2007.

- "Graphical System Design"
  David Fuller, National Instruments, September 26, 2007.

- "Stochastic Omega-Regular Games"
  Krishnendu Chatterjee, UC Berkeley, September 25, 2007.

- "A Multi-Threaded Reactive Processor"
  Reinhard von Hanxleden, Christian-Albrechts-Universitat (CAU) Kiel, September 18, 2007.

- "The Timing Definition Language (TDL) domain in Ptolemy"
  Stefan Resmerita, University of Salzburg, September 13, 2007.

- "Problems in Resource Modeling and Scheduling for Embedded Systems"
  Feng Zhao, Microsoft Research, September 11, 2007.

- "Symbolic Reachability Analysis of Lazy Linear Hybrid Automata"
  Susmit Jha, UC Berkeley, September 4, 2007.

- "A Formal Framework for the Correct-by-construction and Verification of Distributed Time Triggered Systems"
  Dr. Ramesh, GM India Science Lab, August 28, 2007.

4.7.2 Workshops and Invited Talks

In addition to the below invited and workshop organizational activities, Chess faculty have delivered numerous plenary talks, invited talks, as well as informal dissemination of Chess goals and research.

- "Grand Challenges for Real-Time Systems"
  Thomas A. Henzinger, keynote lecture, 20th Euromicro Conference on Real-Time Systems (ECRTS), Prague, Czech Republic, July 2008.

- "Challenges in Embedded Systems Design: Predictability and Robustness"
  Thomas A. Henzinger, invited lecture, Royal Society Meeting: From Computers to Ubiquitous Computing, London, United Kingdom, March 2008.

- "Three Sources of Infinity in Computation: Nontermination, Real Time and Probabilistic Choice"
  Thomas A. Henzinger, keynote lecture, First International Conference on Infinity in Logic and Computation (ILC), Cape Town, South Africa, November 2007.

- "Quantitative Generalizations of Languages"
  Thomas A. Henzinger, keynote lecture, 11th International Conference on Developments in Language Theory (DLT), Turku, Finland, July 2007.

- "Modeling, Verification, and Synthesis of Component Interfaces"
  Thomas A. Henzinger, invited tutorial, 19th International Conference on Computer-Aided Verification (CAV), Berlin, Germany, July 2007.

- "The Embedded Systems Design Challenge"
  Thomas A. Henzinger, keynote lecture, 12th International Workshop on Formal Methods for Industrial-Critical Systems (FMICS), Berlin, Germany, July 2007.

- " Using Mathematical Models to Understand Planar Cell Polarity "
  Claire J. Tomlin, plenary talk, International Conference on Systems Biology, Long Beach, October 2007.

- " Mathematical Models for Protein Regulatory Networks "
  Claire J. Tomlin, plenary talk, International Federation of Automatic Control, Nonlinear COntrol Systems Workshop, Pretoria, South Africa, August 2007.

- "Embedded Intelligence "
  Shankar Sastry, plenary talk, IEEE CASE Conference, Tempe, AZ, September 2007.

4.7.3 General Dissemination

The Chess website, http://chess.eecs.berkeley.edu, includes publications and software distributions. In addition, as part of the outreach effort, the UC Berkeley introductory signals systems course, which introduces hybrid systems, is available.

4.8 Other Specific Products

The following software packages have been made available during this review period on the Chess website, http://chess.eecs.berkeley.edu:

- The Checker for Interface Compatibility (CHIC) is a modular verifier for behavioral compatibility checking of software and hardware components. The goal of CHIC is to be able to check that the interfaces for software or hardware components provide guarantees that satisfy the assumptions they make about each other. CHIC supports a variety of interface property specification formalisms: synchronous assume/guarantee interfaces, resource interfaces, web service interfaces, etc. The latest release, CHIC-1.2 was made available on May 30, 2008 and may be found at: http://www.eecs.berkeley.edu/ arindam/chic/

5 Contributions

This section summarizes the major contributions during this reporting period.

5.1 Within Discipline

5.1.1 Hybrid Systems Theory

- We have worked with our definition of an operational semantics for hybrid systems in the current and next generation of toolsets to reflect these semantics.
- We have developed algorithms for computing the real value of discounted properties, and continued investigation of their application.
- We have matured a theory of a homology theory of hybrid systems which enables elegant characterization of Zeno and other qualitative properties of hybrid systems.
- We have improved on the best known algorithms for finding strategies for the control of stochastic hybrid systems.
- We have continued development of a toolbox using ellipsoidal methods to calculate reach sets for linear dynamic systems, and begun to apply those to hybrid systems.
- We have developed an extensive theory of two and multi person stochastic games with extensions of notions of safety and almost safety in a number of important directions.
- We have continued to apply and study stochastic hybrid systems within the domain of biological systems.
- We are developing a static analysis mechanism that infers the common causality properties of a modal model from those of its modes. The result of the static analysis is conservative, but provides safety guarantees.
- We have continued in our broad initiative to support tool chains in hybrid systems under semantic anchoring and model transformations.

- We derived verifiable necessary and sufficient conditions on when composition preserves semantics for a heterogeneous network of embedded systems.
- We have formally proved the benefits of the logical execution time (LET) model in terms of composability over traditional real-time models.
- We have developed a technique to extend the simulation of a hybrid system past its Zeno point, reducing the computational burden past that point and revealing the complete behavior of the system.

5.1.2 Model-Based Design

- We have developed the first release of a semantic anchoring tool suite, and have demonstrated the use of the tool infrastructure in specifying the semantics of hierarchical state automata.
- Using various specifications of timed automata, we have examined approaches for defining semantic units. We demonstrated the concepts with developing a semantic unit for timed automata and showed the anchoring of UPAAL and IF to this common semantic unit.
- We started investigating the problems of defining semantics for heterogeneous modeling languages, and began establishing a composition theory for semantic units.
- Applying our ongoing work on metamodeling, we have continued development on semantic anchoring for model-based development. Specifically, we have extended the semantic anchoring framework to heterogeneous behaviors.
- We have continued to demonstrate our defined agent algebras as a formal framework for uniformly representing and reasoning about models of computation used in the design of hybrid and embedded software systems.
- We have continued to demonstrate our theoretical and compositional framework for reasoning about causality in components which are composed under concurrent models of computation.
- We have extended our previously developed tagged-signal model for concurrent models of computation to represent the semantics of globally asynchronous, locally synchronous systems built upon loosely time-triggered architectures.
- We have continued to maintain a language and a suite of supporting tools for the specification of model transformations based on graph rewriting.
- We have continued to use our approach to model synthesis based on patterns specified formally as metamodels.
- We have developed an interface theory based approach to static analysis of actor models through composition. It results in an automaton which will contain information used for further static analysis of a composed actor model.
- We have developed a new component model for timed models of computation such as discrete event, continuous time, hybrid systems, and synchronous/reactive models.

- We have built a scalable and formal specification language for embedded systems which can use constraint checking to auto-generate parts of a specification and to approximate the correctness of the specification without invoking verification tools

5.1.3 Advanced Tool Architectures

- We have further developed the code generation approach based on component specialization by developing a formal framework for reasoning about reconfiguration in embedded software.

- We have continued to improve the performance and feature set of the Metropolis framework.

- We have further developed our notion of interface theories to support reasoning about heterogeneous component composition and about the dynamics of models of computation.

- We formulated and solved the task allocation problem for a popular multithreaded, multiprocessor embedded system, the Intel IXP1200 network processor.

- We have continued to investigate interests in fault-tolerant systems by developing new modeling languages which simulate and trace faults in a system.

- We have continued development of the Ptolemy II tool suite, including HyVisual, VisualSense, and Viptos tools for hybrid systems, sensor networks, and NesC-based wireless sensor programming.

- We have shown how to guarantee type-safety in legacy C programs and verify memory safety in the assembly code.

- We have strengthened our understanding of discounted reward objectives to yield real-numbered quantities (e.g., power consumption) that can be expressed during verification.

5.1.4 Experimental Research

- We have extended model predictive control for hybrid systems with a finite control set to develop air and water recovery systems for the NASA Advanced Life Support (ALS) system for long-duration missions.

- We have begun to apply our previous work on safe set calculations to the Autonomous Aerial Refueling (AAR) while in formation problem.

- We have deployed the Metropolis platform-based design methodology for use on various veitronics problems of interest to Toyota, GM, and BMW.

- We have continued development, and deployed a modeling environment for wireless sensor networks. These have been used to simulate detection of a dirty bomb.

- We have developed new programming models for sensor networks that build on the popular TinyOS models.

- We have shown how compositional technologies can be used to produce an autonomous helicopter in the loop with a camera to choose a landing zone, and physically land the vehicle.
- We have used reachability to perform analysis of the cold start problem and shown anticipated reduction in raw hydrocarbon emissions during warm-up using a hybrid systems model.
- We have shown how fault tolerant data flow can be used to synthesize real-time feedback controllers for safety critical applications.
- We have shown that hybrid systems theory can be coupled with Lagrangian methods to produce reduced state-space expressions of computationally difficult problems, such as the motion of a bipedal walker.

5.2 Other Disciplines

- We developed new efficient algorithms for solving stochastic games, which have applications in other fields such as economics and biology.
- We contributed to scientific interdisciplinary information sharing through collaboration and major contribution to the framework of the Kepler Scientific Workflow project.
- We have shown that hybrid systems theory can be coupled with Lagrangian methods to produce reduced state-space expressions of computationally difficult problems, such as the motion of a bipedal walker.

5.3 Human Resource Development

Several panels in important conferences and workshops pertinent to embedded systems (e.g., DAC, ICCAD, HSCC, EMSOFT, CASES, and RTSS) have pointed out the necessity of upgrading the talents of the engineering community to cope with the challenges posed by the next generation embedded system technology. Our research program has touched many graduate students in our institutions and several visiting researchers from industry and other Universities so that they now have a deep understanding of embedded system software issues and techniques to address them.

Specifically, our directors played a major role in the development of workshops and briefings to executives and researchers in the avionics industry to motivate increased research spending due to an anticipated drop in research funds available to train graduates in embedded software and embedded systems. One particular intersection with our efforts is the Software Producibility Initiative out of the Office of the Secretary of Defense.

The industrial affiliates to our research program are increasing and we hope to be able to export in their environments a modern view of system design. Preliminary feedback from our partners has underlined the importance of this process to develop the professional talent pool.

5.4 Integration of Research and Education

In this report, we have touched multiple times on research and education especially in the outreach section. In addition, there has been a strong activity in the continued update of the undergraduate course taught at Berkeley on the foundations of embedded system design. The graduate program at Berkeley and at Vanderbilt has greatly benefited from the research work in the ITR. EE249 at Berkeley has incorporated the most important results thus far obtained in the research program. EE 290 A and C, advanced courses for PhD students, have featured hybrid system and the interface theories developed under this project. EE219C, a course on formal verification, has used results from the hybrid theory verification work in the program. Finally, many final projects in these graduate courses have resulted in papers and reports listed in this document. The course EE291E on Hybrid Systems: Computation and Control is jointly taught at Berkeley and Vanderbilt and is benefiting a great deal from comments of students as far as the development of new text book material.
In addition to the influence on graduate students, we have endeavored to show hybrid and embedded systems as emerging research opportunities to undergraduates. We have also demonstrated that for advanced undergraduates these topics are not out of place as senior design courses, or advanced topics courses, which may in the future lead to the integration of these as disciplines in engineering across a broader reach of universities.

5.5 Beyond Science and Engineering

Embedded systems are part of our everyday life and will be much more so in the future. In particular, wireless sensor networks will provide a framework for much better environmental monitoring, energy conservation programs, defense and health care. Already in the application chapter, we can see the impact of our work on these themes. In the domain of transportation systems, our research is improving safety in cars, and foundationally improving control of energy conserving aspects such as hydrocarbon emissions. Future applications of hybrid system technology will involve biological systems to a much larger extent showing that our approach can be exported to other field of knowledge ranging from economics to biology and medicine. At Berkeley, the Center for Information Technology Research in the Interest of Society is demonstrating the potential of our research in fields that touch all aspects of our life. Some key societal grand challenge problems where our ITR research is making a difference includes health care delivery, high confidence medical devices and systems, avionics, cybersecurity, and transportation.

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