## SUMMARY OF RESEARCH ACTIVITIES

My group's research addresses problems of control and automation and examines ways to design engineering systems that will exhibit high degree of autonomy in performing useful tasks. Application areas include manufacturing, transportation and power systems as well as computer and communication networks. Research work includes analysis of behavior and design of control strategies for complex autonomous, intelligent, learning and reconfigurable systems.

Recent research focuses on networked embedded systems and addresses problems in the interdisciplinary research area of systems and control, computing and communication networks, and on hybrid and discrete event dynamical systems.

In **Publications**, our published work is accessible to download. The list of publications is organized by areas:
*Control and Networks*
*Distributed Multi-agent Systems*
*Hybrid Control Systems*
*Supervisory Control of Discrete Event Systems*

In **Archived Publications**, earlier work may be found including publications on *Autonomous Intelligent Control* and on the *Feedback Control of Linear Systems*.

Additional information regarding research topics and contributions is accessible via the webpages of **Books** and **Special Issues**.

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## RESEARCH HIGHLIGHTS AND PERSONAL REFLECTIONS

First, a few words about my research vision and the way I work, so to make clearer (especially to future PhD students) the reasons for selecting the specific areas of research described below.

I work closely with students in research and I allow significant freedom in the selection of PhD research topics. I encourage individuality and excellence, and I expect love of the subject, enthusiasm and intellectual curiosity. I think the Systems and Controls area is a truly great research area and I expect my students to feel the same way.

I try to be responsive to future application needs, as in my opinion this is where a University should be conducting its research, keeping an eye down the road, and focusing primarily on defining and articulating new methods and solving new problems in novel ways, without excluding of course extending a helping hand if requested by industry practitioners. The concern for addressing effectively future research needs in applications has led me to move onto novel research areas with my group and play leading roles in those areas.

In the late 80s my group helped establish Autonomous Intelligent Control in the mainstream control research community; in the early 90s, we introduced Supervisory Control of Discrete Event Systems (DES) using Petri nets; in the mid-90s we helped establish Hybrid Control Systems and influenced its research directions; more recently we are involved in Networked Control Systems and in the Distributed Control of Multi-agent Systems.

There is a strong common thread that permeates all these research areas and led us to the study of these research topics. We have been pursuing a *Quest for Autonomy* in complex systems, wanting to build Intelligent, High Autonomy control systems. In systems with high degree of autonomy, the higher levels of control hierarchy are described by discrete event system models, automata or Petri nets; this led us to the study of *Supervisory Control of DES via Petri nets*. Lower in the control hierarchy, DES systems interact with continuous control systems described via differential equations; this led us to the study of *Hybrid Systems* and to interactions with computer scientists. Advances in technology make it now possible to embed significant computing intelligence and communication capabilities in distributed fashion and at low cost, close to the application where sensing, processing and control is needed, thus reducing the need for centralized control. This has led us to the study of *Networked Embedded Sensing and Control Systems* and to the study of Consensus and other problems in Distributed Systems, using methodologies that lie at the intersection of systems and control, communication networks and computing.

*Our Quest for Autonomy is continuing!*

## RESEARCH HIGHLIGHTS

Below some of my group's research areas and contributions are briefly described. The research topics are arranged from the more recent to the earliest.

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## NETWORKED EMBEDDED CONTROL SYSTEMS

Networked sensing and control systems are becoming increasingly important in many application domains including transportation, manufacturing, defense, and health related areas. It is now possible to place low cost devices with significant computing and communication capabilities in distributed fashion and connect them via wired and wireless networks, so to cooperate working together towards common goals. This area uses methodologies from control systems, communication networks and computing.

The networked nature of the system raises a number of issues that relate to traditional issues encountered by all distributed systems, with the addition of the complications introduced by shared digital networks where the information is sent in data packets. Note also that future networks of embedded processors may include several hundred to several thousand computing nodes distributed perhaps over wide areas and realized via inexpensive MEMS–based sensors and actuators.

There is tight interaction between the digital processors and the physical world and this raises a number of issues that relate to the real-time requirements on system performance, to the hybrid nature and inherent uncertainty of the interaction with the physical world, and to the requirement for high autonomy. Networked embedded sensing and control systems are *Cyber-Physical Systems (CPS)* and there is increasing emphasis on better understanding the interactions between the engineered, digital computing systems and the physical, analog world which is typically complex and uncertain.

Since the system is embedded, the user and system do not directly interact. This means that the system must possess a significant degree of autonomy with regard to the monitoring and maintenance of its own health. The embedded system interacts with the physical world and this interaction introduces hybrid dynamics and injects significant uncertainty into the system. Assumptions that are valid at compile-time may not be valid a run-time. Components degrade over time. The physical world is not static and may even be malicious in its dealings with the embedded system. Finally, the real world marches to real-time and this means that our embedded processors must satisfy hard and soft real-time deadlines.

The network will exhibit a high degree of concurrency. The impact of this concurrency is to generate a state-space explosion problem that can limit our ability to analyze such systems. This means that any analysis approach must demonstrate a high degree of scalability. The networked system is decentralized and this means that we cannot expect any single process to know the global state at a given instant in time. As a result, control and supervision methods will need to rely on local partial state information. The networked system is often composed of units from a wide variety of vendors. This means that these systems will be open and we need to ensure that the protocols and software we develop are portable across different hardware and software platforms. Finally, since processor failures will occur we need fault-tolerant methods for re-inserting, for example a reset processor into the network. This requirement for dependability also brings up security issues. How do we identify and isolate malicious processors in the network? In dealing with a network of embedded systems, these distributed computing issues and the embedded control system issues must be addressed. All of the preceding issues are present in the design and analysis of embedded systems.

In our group, we have studied sensor networks, networked control systems and distributed systems. We have introduced a novel *Model Based* approach to networked control that is application realistic and transparent and we have extended it to include *Intermittent Feedback* control. We have studied *Quantization* in networked system and we have used the notion of *Passivity* to design stable networked systems. We have applied some of these results to *Tele-operation*. We have also studied *Distributed Contro*l systems based on *Spatial Invariance* and we have made contributions to the *Consensus* problem.

See **Publications**-*Control and Networks; Distributed Multi-agent Systems*

See also the Special Issues on Networked Control Systems in the *IEEE Transactions on Automatic Control,* September 2004, and in the Proceedings of the IEEE, January 2007 with P.J Antsaklis and J. Baillieul as Guest Editors.

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**HYBRID AND SWITCHED DYNAMICAL SYSTEMS**

A hybrid dynamical system is a system where the behavior of interest is determined by interacting continuous and discrete dynamics. In a manufacturing process for example, parts may be processed in a particular machine, but only the arrival of a part triggers the process; that is, the manufacturing process is composed of the discrete, event-driven dynamics of the parts moving among different machines and the continuous, time-driven dynamics of the processes within particular machines. The need for advanced computer control of continuous processes in areas such as manufacturing, communication networks and industrial processes provides strong motivation for the study of modeling, design, verification and control of hybrid dynamical systems that include both continuous and discrete dynamics that interact with each other. Many times the continuous and discrete parts of the processes of interest may be studied independently, but when there are strong interactions among these continuous and discrete components or tight design specifications to be met, the hybrid nature of the processes must be taken explicitly into account. Only then problems such as optimization of the whole manufacturing process may be addressed in a more meaningful manner.

In our approach we have identified and studied fundamental concepts that arise at the interface of the continuous and discrete dynamics, such as non-determinism in the DES models derived using discrete abstractions. We have derived conditions for the *Stabilizability of Uncertain Switched Systems* and we have made contributions in the *Optimal Contro*l of switched systems. Throughout our work we have emphasized *Synthesis* methodologies and have derived controllers for hybrid systems. Our trademark approach is our *Supervisory Hybrid Control* approach that is based on discrete abstractions of the continuous dynamics.

See **Publications**-*Hybrid Control Systems*

See also the Springer-Verlag books *Hybrid Systems II*, *Hybrid Systems IV*, and *Hybrid Systems V*, and the Special Issues in the *Proceedings of the IEEE*, July 2000, in the *Journal on Discrete Event Dynamic Systems*, June 1998 and in the *IEEE Transactions on Automatic Control*, April 1998. The Special Issue on Hybrid Systems: Theory and Applications of the *Proceedings of the IEEE* (July 2000) consists of fourteen invited papers, and it is used as a teaching supplement by several leading research groups around the world.

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**SUPERVISORY CONTROL OF DISCRETE EVENT DYNAMICAL SYSTEMS USING PETRI NETS**

Discrete Event System (DES) models may be used to describe the dynamic behavior of manufacturing processes, chemical processes, computer and communication processes when there are event driven processes that need to be controlled. Motivated by the generality and relative simplicity of Petri net models of DES and inspired by chemical engineering applications of Petri net modeling, we introduced and developed a novel computationally efficient simple approach to control of DES. Our approach represents significant improvement in the control of DES area, which at that time had reached a stage of theoretical maturity, but with methodologies that were not easy to use in large systems.

Based on algebraic representations of *Petri nets* we were able to derive a truly elegant approach to the *Supervisory Control of DES*. The controller is based on the idea of place invariants of the Petri net and it consists only of places and arcs. The controller is maximally permissive. This method is based on matrix manipulations and is computationally very efficient. It can accommodate constraints written as Boolean logic formulas in the conjunctive normal form of algebraic inequalities that contain elements of the marking and/or the firing vectors. Our design approach enforces linear inequality constraints on the markings of the plant. Such inequality constraints can model a variety of important control specifications including forbidden state and general mutual exclusion constraints, finite resource management and allocation constraints, liveness and deadlock avoidance constraints. This approach is very attractive as the resulting controller is a Petri net that consists only of places and arcs and its size is proportional to the number of constraints. The controller is described by an auxiliary Petri net connected to the plant's transitions, providing a unified Petri net model of the closed loop system. Standard tools for Petri nets can then be used to further analyze and study the supervised plant. This design approach is also most attractive because it is transparent, modular, computationally efficient and well suited for on-line reconfigurable control. Several extensions to decentralized control and generalizations have been derived.

See **Publications**-*Supervisory Control of Discrete Event Systems*

See also the books *Supervisory Control of Discrete Event Systems using Petri Nets* (by Moody & Antsaklis, Kluwer 1998), and *Supervisory Control of Concurrent Systems* (by Iordache & Antsaklis, Birkhauser 2005).

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## INTELLIGENT CONTROL FOR HIGH AUTONOMY SYSTEMS

**Intelligent Autonomous Control.** Made contributions which helped define the field and its foundations. See for example P.J.Antsaklis and K.M.Passino, Eds, *An Introduction to Intelligent and Autonomous Control*, 448 pages, Kluwer Academic Publishers, 1993; also P. J. Antsaklis, "Defining Intelligent Control", *IEEE Control Systems Magazine*, pp. 4-5 & 58-66, June 1994.

**Planning and Control**. Among the first to identify the relations between these areas. Also contributed to the theory of discrete search (A* algorithm) and formulated and solved optimal control problems in logical discrete event systems. See for example K. M. Passino and P. J. Antsaklis, "A Metric Space Approach to the Specification of the Heuristic Function for the $A^*$ Algorithm", *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. 24, no 1, pp 159-166, Jan 1994.

**Neural Networks**. Developed algorithm to construct and train feedforward neural networks. The algorithm applies to networks with both continuous or discrete activation functions. It is based on solving linear systems of equations and it is one of the fastest algorithms reported. See J. O. Moody and P. J. Antsaklis, "The Dependence Identification Neural Network Construction Algorithm", *IEEE Transactions on Neural Networks*, Vol 7, No 1, pp. 3-15, January 1996; also P.J. Antsaklis, "Neural Networks in Control Systems", Guest Editor's Introduction, *IEEE Control Systems Magazine*, Vol.10, No.3, pp.3-5, April 1990; and Vol.12, No.3, pp.8-10, April 1992.

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## FEEDBACK CONTROL OF LINEAR SYSTEMS

**Parameterization of all Feedback Stabilizing** Controllers. Among the first to establish the relation between Youla's parameterizations and the Diophantine equation in the late 70s; this was accomplished using the polynomial matrix representation of systems. Explained relation between proper and stable factorizations of a system transfer function and its internal descriptions. Some of these results are included in Chaprer 7 of the *Linear Systems* book (with A.N. Michel; McGraw-Hill, 1997 and Birkhauser, 2005).

**Theory of Polynomial Matrix Interpolation**. It not only extends the classical polynomial interpolation results but its applications to solving polynomial matrix equations have been proved to have excellent numerical properties. See for example P. J. Antsaklis and Z. Gao, "Polynomial and Rational Matrix Interpolation: Theory and Control Applications", *International Journal of Control*, vol 58, no. 2, 349-404, August 1993; also Matlab polynomial control design package by Sebek and Kwakernaak called The Polynomial Toolbox.

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