ANTSAKLIS GROUP - SUMMARY OF RESEARCH ACTIVITIES

My research 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 Cyber-Physical Systems (CPS) (that consist of a large number of heterogeneous, cyber, physical networked embedded subsystems with sometimes a human operator in the loop) and addresses problems in the interdisciplinary research area of control, computing and communication networks, and on hybrid and discrete event dynamical systems.

****

RESEARCH HIGHLIGHTS

Being responsive to future application needs is very important, 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 working with industry practitioners on near term research needs. 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.

My early research focused on the Feedback Control of Multi-input, Multi-output Linear Time-invariant systems using Polynomial Matrix descriptions (mid to late 70s and 80s). There I contributed to understanding and solving several feedback problems, including decoupling and regulation with internal stability, design of response using two-degrees of freedom controllers, control reconfiguration, polynomial matrix interpolation. Especially noteworthy are the contributions to characterizing all stabilizing controllers using dual prime polynomial matrix descriptions and polynomial matrix transfer function factorizations.

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 and the work in this area is continuing today; we have been involved in Networked Control Systems since the early 00s, also in the Distributed Control of Multi-agent Systems; we have developed a powerful approach to control of Networked Systems, that uses explicit plant models in the feedback loop-this Model-Based Approach to control provides significant benefits in reduction of the use of the network.

Since the mid-00s we have been focusing our research in Cyber Physical Systems (CPS), which combines all of the research areas mentioned previously. In fact my group was one of a handful of research groups that were early active supporters of CPS and helped establish CPS as a highly relevant and important research area in the US and abroad. I was very involved with the 2007 PCAST (US President's Council of Advisors on Science and Technology) report on research priorities in networking and information technology in the US, which contributed in a substantial way to recognizing CPS as highly important research area. In CPS, which are typically hybrid, networked, complex and dynamically evolving systems, we have been using energy like notions such as Passivity and Dissipativity to attain robust stability and performance.

There is a strong common thread that permeates all my research areas, a thread which in fact has led me to the study of all these research topics. I 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 typically described by discrete event system models, such as automata or Petri nets, which led me to conducting research in the supervisory control of DES via Petri nets. Lower in the control hierarchy, DES systems interact with continuous control systems described via differential equations and this led me to the study of Hybrid Systems and to close interactions with computer scientists. Advances in technology make it now possible to embed significant computing intelligence and communication capabilities at low cost in distributed fashion 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 Cyber Physical Systems,* and to the study of 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!*

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. The best way to get into the details is of course via our publications.

Our work has been recognized and used by researchers. The publications of my research group have been cited over 30,000 times (600 publications, h-index 78 in August 2021). More than 65 of the publications have been cited from 100 to 2,400 times each, which shows the wide distribution of the citations.

****

CYBER PHYSICAL SYSTEMS

Cyber-physical systems (CPS) are physical, biological and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core. As computers become ever-smaller, faster and more efficient, and communication networks become better and ever- cheaper, computing and communication capabilities are being embedded in all types of objects and structures in the physical environment. This intimate coupling between the cyber and physical is being manifested from the nano-world to large-scale wide-area systems of systems; and at multiple time-scales. There are several technological and economic drivers for this trend: the decreasing cost of computation, networking, and sensing, a variety of social and economic forces which will require us to use national infrastructures more efficiently, and environmental pressures which mandate the rapid introduction of technologies to improve energy efficiency and reduce pollution; also, as the national population ages, we will need to make more efficient use of our health care systems, ranging from facilities to medical data and information. Applications with enormous societal impact and economic benefit will be created. According to NSF, research advances in cyber-physical systems promise to transform our world with systems that respond more quickly (e.g., autonomous collision avoidance), are more precise (e.g., robotic surgery and nano-tolerance manufacturing), work in dangerous or inaccessible environments (e.g., autonomous systems for search and rescue, firefighting, and exploration), provide large-scale, distributed coordination (e.g., automated traffic control), are highly efficient (e.g., zero-net energy buildings), augment human capabilities, and enhance societal well being (e.g., assistive technologies and ubiquitous healthcare monitoring and delivery).

Cyber-physical systems will transform how we interact with the physical world just like the Internet transformed how we interact with one another.

Notre Dame has had significant presence in this research area since its inception. In fact, Panos Antsaklis was a member of a 2007 committee of the President's Council of Advisors in Science and Technology (PCAST) that recognized the importance of CPS to society and made it number one national priority in networking and information technology federal research funding. Activities include:

- Panos J. Antsaklis, "Goals and Challenges in Cyber-Physical Systems Research," Editorial of the Editor-in Chief, Special Issue on the Control of CPS, IEEE Trans. on Auto. Control, December 2014.
- Science Keynote Speaker at the 2012 NSF CPS PI Meeting in Washington D.C., October 2012.
- Organizer of the Control of Cyber-Physical Systems Workshop at the University of Notre Dame London Centre October 20-21, 2012. (http://controls.ame.nd.edu/mediawiki/index.php/London_CPS_Workshop)

- Keynote Address at the 31st Chinese Control Conference (CCC'12) "Cyber-Physical Systems Design Using Dissipativity," Hefei, China, July 25 -27, 2012.
- Keynote Address at the 2009 American Control Conference (ACC2009), "From Hybrid to Networked Cyber-Physical Systems," St. Louis, Missouri, USA, June 10-12, 2009.

Some CPS Issues

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. 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. CPS systems may be embedded, and so the user and system may 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 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 at run-time. Components degrade over time. The physical world is not static and may even be malicious. Finally, the real-world marches to real-time and this means that our embedded processors must satisfy hard and soft real-time deadlines.

Our CPS research has been focusing on ways to build systems from components in ways that guarantee certain properties. We have been using the energy concepts of passivity and dissipativity of continuous and discrete-time systems, of networks and of hybrid dynamical systems. We have been focusing on interconnected networked systems using passivity indices, QSR-dissipativity, and wave transformations in networks and we have made important contributions to preserving passivity in approximate models after for example quantization, linearization, order reduction, etc; we have studied event-driven feedback systems, systems in cascade and stability and synchronization in distributed control systems. In addition we have been extending these passivity and dissipativity concepts to switched systems, and also to hybrid and discrete-event systems. We have also worked on experimentally determining passivity indices, which brings in the issue of mathematical modeling versus actual implementation and to what extent properties are preserved.

Some of the approaches used by the research team that look into a new science of integration for CPS under a CPS Large project including passivity are outlined in:

- Janos Sztipanovits, Xenofon Koutsoukos, Gabor Karsai, Nicholas Kottenstette, Panos Antsaklis, Vijay Gupta, Bill Goodwine, John Baras, and Shige Wang, "Toward a Science of Cyber-Physical System Integration," Proceedings of the IEEE, Special Issue on Cyber-Physical Systems (CPS), pp. 29-44, 2012.

****

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 sensors and actuators.

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 and Cyber-Physical Systems. See 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:

- P.J. Antsaklis and J. Baillieul, Eds, 'Guest Editorial, Special Issue on 'Networked Control Systems,' *IEEE Transactions on Automatic Control,* Vol.49, No.9, pp. 1421-1423, September 2004.
- Panos J. Antsaklis and J. Baillieul, “Scanning the Issue: Special Issue on Technology of Networked Control Systems," P. J. Antsaklis and J. Baillieul Eds., *Proceedings of the IEEE*, Vol.95, No. 1, pp. 5-8, January 2007.
- John Baillieul and Panos J. Antsaklis, "Control and Communication Challenges in Networked Real-Time Systems," in the Special Issue on "Technology of Networked Control Systems," *Proceedings of the IEEE*, Vol.95, No. 1, pp. 9-28, January 2007.

In our group, we have studied sensor networks, networked control systems and distributed systems. We have introduced a very promising novel *Model Based* approach to networked control that is application realistic and transparent and we have extended it to include *Intermittent Feedback* control. Using this Model-Based approach we have studied the effects of dropped packets and limited bandwidth on stability and performance issues and we have studied the effects of quantization and event-triggered feedback. The approach is practical and efficient, stability conditions are if and only if (for LTI systems) and the method has been extended and used in applications.

The approach of Model-Based Control is described at length in the book titled *Model-Based Control of Networked Systems* by Eloy Garcia, Panos Antsaklis, Luis Montestruque, Springer/Birkhauser 2014.

We have also studied *Distributed Contro*l systems and we have made contributions to the *Consensus* problem. We have used the energy like concepts of passivity and dissipativity to study systems consisting of heterogeneous interconnected components.

****

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.

We have made contributions which helped define the field. We developed problem formulations, established some of the key concepts and introduced control synthesis methodologies. 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, if and only if conditions, and we have made contributions in the optimal control 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.

Our work is described in several books I edited: See the Springer-Verlag books *Hybrid Systems II*, *Hybrid Systems IV*, and *Hybrid Systems V*; and in 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 has been used as a teaching supplement by several leading research groups around the world.

There is an upcoming textbook (2021) titled
Hybrid Dynamical Systems: Foundations ad Methods by Hai Lin and Panos Antsaklis (Springer).

An early more focused version appeared in:
H. Lin and P. J. Antsaklis, "Hybrid Dynamical Systems: An Introduction to Control and Verification," Foundations and Trends in Systems and Control, Now Publishers, vol. 1, no. 1, pp. 1-172, Mar. 2014.

****

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 transparent and computationally very efficient and can be used to avoid deadlock. The approach opened new venues for research in the supervisory control of DES. It was recently used by the U of Michigan group to identify potential faults in commercial code and is currently being used to develop a systematic method for concurrent programming.

The method 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.

The DES contributions are described in two books the more recent being *Supervisory Control of Concurrent Systems: A Petri Net Structural Approach,* Iordache & Antsaklis Birkhauser 2005. It describes a novel, powerful and practical method with emphasis on deadlock avoidance and decentralized supervision. See also the book *Supervisory Control of Discrete Event Systems using Petri Nets,* Moody & Antsaklis, Kluwer 1998.

****

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*, pp. 448, Kluwer Academic Publishers, 1993; also P. J. Antsaklis, "Defining Intelligent Control-Report on the CSS Task Force on Intelligent Control," *IEEE Control Systems Magazine*, pp. 4-5 & 58-66, June 1994.

A hierarchical functional architecture was adopted and it was clearly shown that for controlling different functions of a system and introducing higher degrees of autonomy, one needed to bring in methods beyond traditional control methods, methods that involved, planning, learning, failure diagnosis and isolation etc. So higher autonomy is the goal and for high autonomy one may need methods that are referred to as intelligent and so the term Intelligent Control. This way of thinking led me to studying Discrete Event Systems, Hybrid Systems and Networked Control as they are important in accomplishing higher degrees of autonomy. For an update see Panos Antsaklis. "Autonomy and Metrics of Autonomy," Annual Reviews in Control, Vol. 49, pp. 15-26, 2020. https://doi.org/10.1016/j.arcontrol.2020.05.001 and the references therein.

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 iwas one of the fastest algorithms reported at the time. 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.

I was also the Guest Editor of the 1990 and 1992 *Special Issues on Neural Networks in Control Systems* of the IEEE Control Systems magazine (CSM) and the Guest Editor of the 1995 *Special Issue on Intelligence and Learning* in the IEEE CSM.

****

FEEDBACK CONTROL OF LINEAR SYSTEMS

Parameterization of all Stabilizing Feedback Controllers. Among the first to establish the relation between Youla's parameterizations and the polynomial matrix Diophantine equation; this was accomplished using the polynomial matrix representation of systems. A particularly simple way to derive these parameterizations was based on the new concept of dual prime polynomial matrix factorizations as described in P. J. Antsaklis, "Some Relations Satisfied by Prime Polynomial Matrices and their Role in Linear Multivariable System Theory," *IEEE*

Trans. Automatic Control, Vol. AC-24, No. 4, pp. 611-616, Aug. 1979 (See also T. Kailath, Linear Systems, pp.539-540, Prentice-Hall, 1980). This dual prime approach has been the standard approach to the subject. Explained relation between proper and stable factorizations of a system transfer function and its internal descriptions. Many of these results are included in Chapter 7 of the *Linear Systems* book (with A.N. Michel; McGraw-Hill, 1997 and Springer, 2006).

He made significant contributions to the Output Regulation with Internal Stability problem, the Decoupling problem, the Reconfigurable control problem.

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.

Several of these results may be found in the graduate textbooks *Linear Systems* (with A.N. Michel; McGraw-Hill, 1997 and Springer, 2006) and *A Linear Systems Primer* (with A.N. Michel; Springer, 2007).

****