REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-06-0126

1. REPORT DATE *(DD-MM-YYYY)* 31-March 2006	2. REPORT TYPE Final Performance Report	3. DATES COVERED *(From - To)* 1 Mar 2003 - 31 Dec 2005
4. TITLE AND SUBTITLE A Network Thermodynamic Framework for the Analysis and Control Design of Large-Scale Dynamical Systems		5a. CONTRACT NUMBER 5b. GRANT NUMBER F49620-03-1-0178 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Wassim M. Haddad Quirino Balzano		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Georgia Institute of Technology School of Aerospace Engineering Atlanta, GA 30332-0150		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) The Air Force Office of Scientific Research 875 N. Randolph Street, Suite 325, Room 3112 Arlington, VA 22203-1768 Col. Sharon Heise		10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR/NM 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A: Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The main goal of this report is to summarize the progress achieved under the program during the past three years. Since most of th
technical results appeared or soon will appear in over 100 archival journals and conference publications, we shall only summarize
results and remark on their significance and interrelationship.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF	19a. NAME OF RESPONSIBLE PERS
					Wassim M. Haddad
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	UL		19b. TELEPHONE NUMBER *(include ar* 404-894-1078

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

A Network Thermodynamic Framework for the Analysis and Control Design of Large-Scale Dynamical Systems

Final Report
F49620-03-1-0178

by

Wassim M. Haddad

Principal Investigator
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

for

Air Force Office of Scientific Research
875 North Randolph Street, Suite 325, Room 3112
Arlington, VA 22203

Attention

Dr. Sharon Heise

March 31, 2006

Home of the 1996 Olympic Village
Georgia Institute of Technology

School of Aerospace Engineering
Atlanta, Georgia 30332-0150 U.S.A.
PHONE 404-894-1078
FAX 404-894-2760

Contents

1. Introduction

1.1. Research Objectives

As part of this research program we proposed the development of a general analysis and control design framework for large-scale nonlinear dynamical systems. In particular, we concentrate on hybrid control, hierarchical control, impulsive dynamical systems, nonnegative dynamical systems, compartmental systems, large-scale systems, nonlinear switching control, and adaptive control. Application areas include large flexible interconnected space structures, vibration control of aerospace structures, spacecraft stabilization, biological systems, physiological systems, and pharmacological systems.

1.2. Overview of Research

Controls research by the Principal Investigator [1–99] has concentrated on an energy-based thermodynamic stabilization framework for hybrid control design of large-scale aerospace systems. This framework provides a rigorous foundation for developing a unified energy-based (network thermodynamic) analysis and synthesis methodology for large-scale aerospace systems possessing hybrid, hierarchical, and feedback structures. This framework additionally provides a rigorous alternative to designing gain scheduled controllers for general nonlinear dynamical systems by constructing minimal complexity logic-based nonlinear controllers consisting of a number of subcontrollers situated in levels (protocol layers of hierarchies) such that each subcontroller can coordinate lower-level controllers. Correspondingly, the main goal of this research has been to make progress towards the development of analysis and hierarchical hybrid nonlinear control law tools for nonlinear large-scale dynamical systems. This framework provides the basis for developing control-system partitioning/embedding using concepts of energy-based thermodynamic hybrid stabilization for complex, large-scale aerospace systems.

An energy flow modeling framework for large-scale dynamical systems based on thermodynamic principles is developed. In particular, we introduced the notion of a control vector Lyapunov function as a generalization of control Lyapunov functions and show that asymptotic stabilizability of a nonlinear dynamical system is equivalent to the existence of a control vector Lyapunov function. Moreover, using control vector Lyapunov functions, we construct a universal decentralized feedback control law for a decentralized nonlinear dynamical system that possesses guaranteed gain and sector margins in each decentralized input channel. Connections between the recently developed notion of vector dissipativity and optimality of the proposed decentralized feedback control law are also established. In addition, we developed a neural adaptive *output feedback* control framework for adaptive set-point regulation of nonlinear uncertain nonnegative and compartmental systems. The proposed framework is Lyapunov-based and guarantees ultimate boundedness of the error signals corresponding to the system states and the neural network weighting gains. The approach is applicable to nonlinear systems with unmodeled dynamics of unknown dimension and amplitude and rate saturation constraints. The aforementioned design frameworks were applied to control of large-scale flexible structures, control of thermoacoustic combustion instabilities in aeroengines, and active control for operating room hypnosis and intensive care unit sedation.

1.3. Goals of this Report

The main goal of this report is to summarize the progress achieved under the program during the past three years. Since most of the technical results appeared or will soon appear in over 100 archival journal and conference publications, we shall only summarize these results and remark on their significance and interrelationship.

2. Description of Work Accomplished

The following partial research accomplishments have been completed over the past three years.

2.1. Thermodynamics and Large-Scale Nonlinear Dynamical Systems

Modern complex dynamical systems are highly interconnected and mutually interdependent, both physically and through a multitude of information and communication network constraints. The sheer size (i.e., dimensionality) and complexity of these large-scale dynamical systems often necessitates a hierarchical decentralized architecture for analyzing and controlling these systems. Specifically, in the analysis and control-system design of complex large-scale dynamical systems it is often desirable to treat the overall system as a collection of interconnected subsystems. The behavior of the composite (i.e., large-scale) system can then be predicted from the behaviors of the individual subsystems and their interconnections. The need for decentralized analysis and control design of large-scale systems is a direct consequence of the physical size and complexity of the dynamical model.

In particular, computational complexity may be too large for model analysis while severe constraints on communication links between system sensors, actuators, and processors may render centralized control architectures impractical.

In an attempt to approximate high-dimensional dynamics of large-scale structural (oscillatory) systems with a low-dimensional diffusive (non-oscillatory) dynamical model, structural dynamicists have developed thermodynamic energy flow models using stochastic energy flow techniques. In particular, statistical energy analysis (SEA) predicated on averaging system states over the statistics of the uncertain system parameters have been extensively developed for mechanical and acoustic vibration problems. Thermodynamic models are derived from large-scale dynamical systems of discrete subsystems involving stored energy flow among subsystems based on the assumption of weak subsystem coupling or identical subsystems. However, the ability of SEA to predict the dynamic behavior of a complex large-scale dynamical system in terms of pairwise subsystem interactions is severely limited by the coupling strength of the remaining subsystems on the subsystem pair. Hence, it is not surprising that SEA energy flow predictions for large-scale systems with strong coupling can be erroneous.

An alternative approach to analyzing large-scale dynamical systems was introduced by the pioneering work of Šiljak and involves the notion of *connective stability.* In particular, the large-scale dynamical system is decomposed into a collection of subsystems with local dynamics and uncertain interactions. Then, each subsystem is considered independently so that the stability of each subsystem is combined with the interconnection constraints to obtain a *vector Lyapunov function* for the composite large-scale dynamical system guaranteeing connective stability for the overall system. The use of vector Lyapunov functions in large-scale system analysis offers a very flexible framework since each component of the vector Lyapunov function can satisfy less rigid requirements as compared to a single scalar Lyapunov function. Moreover, in large-scale systems several Lyapunov functions arise naturally from the stability properties of each subsystem.

In light of the fact that energy flow modeling arises naturally in large-scale dynamical systems and vector Lyapunov functions provide a powerful stability analysis framework for these systems, it seems natural that dissipativity theory, on the subsystem level, should play a key role in unifying these analysis methods. Specifically, dissipativity theory provides a fundamental framework for the analysis and design of control systems using an input-output description based on system energy related considerations. The dissipation hypothesis on dynamical systems results in a fundamental constraint on their dynamic behavior wherein a dissipative dynamical system can only deliver a fraction of its energy to its surroundings and can only store a fraction of the work done to it. Such conservation laws are prevalent in large-scale dynamical systems such as aerospace systems, power systems, network systems, structural systems, and thermodynamic systems. Since these systems have numerous input-output properties related to conservation, dissipation, and transport of energy, extending dissipativity theory to capture conservation and dissipation notions on the subsystem level would provide a natural energy flow model for large-scale dynamical systems. Aggregating the dissipativity properties of each of the subsystems by appropriate storage functions and supply rates would allow us to study the dissipativity properties of the composite large-scale system using *vector storage functions* and *vector supply rates.* Furthermore, since vector Lyapunov functions can be viewed as generalizations of composite energy functions for all of the subsystems, a generalized notion of dissipativity, namely, *vector dissipativity*, with appropriate vector storage functions and vector supply rates, can be used to construct vector Lyapunov functions for nonlinear feedback large-scale systems by appropriately combining vector storage functions for the forward and feedback large-scale systems. Finally, as in classical dynamical system theory, vector dissipativity theory can play a fundamental role in addressing robustness, disturbance rejection, stability of feedback interconnections, and optimality for large-scale dynamical systems.

In this research [16, 21], we develop vector dissipativity notions for large-scale nonlinear dynamical systems; a notion not previously considered in the literature. In particular, we introduce a generalized definition of dissipativity for large-scale nonlinear dynamical systems in terms of a *vector inequality* involving a vector supply rate, a vector storage function, and an essentially nonnegative, semistable dissipation matrix. Generalized notions of vector available storage and vector required supply are also defined and shown to be element-by-element ordered, nonnegative, and finite. On the subsystem level, the proposed approach provides an energy flow balance in terms of the stored subsystem energy, the supplied subsystem energy, the subsystem energy gained from all other subsystems independent of the subsystem coupling strengths, and the subsystem energy dissipated. Furthermore, for large-scale dynamical systems decomposed into interconnected subsystems, dissipativity of the composite system is shown to be determined from the dissipativity properties of the individual subsystems and the nature of the interconnections. Finally, using vector dissipativity theory, we provide a system-theoretic foundation for thermodynamics. Specifically, using a large-scale dynamical systems theory prospective for thermodynamics, we show that vector dissipativity notions lead to a precise formulation of the equivalence between dissipated energy (heat) and work in a large-scale dynamical system. Next, we give a deterministic definition of entropy for a large-scale dynamical system that is consistent with the classical thermodynamic definition of entropy and show that it satisfies a Clausius-type inequality leading to the law of entropy nonconservation. Furthermore, we introduce a dual notion to entropy; namely, *ectropy*, as a measure of the tendency of a large-scale dynamical system to do useful work and show that conservation of energy in an isolated system necessarily leads to nonconservation of ectropy and entropy. Then, we show that our thermodynamically consistent large-scale nonlinear dynamical system model is *semistable*, that is, it has convergent subsystem energies to Lyapunov stable energy equilibria. In addition, we show that the steady-state distribution of the large-scale system energies is uniform leading to system energy equipartitioning corresponding to a minimum ectropy and a maximum entropy equilibrium state.

2.2. A System Theoretic Foundation for Thermodynamics and its Application to Control of Large-Scale Dynamical Systems

Energy is a concept that underlies our understanding of all physical phenomena and is a measure of the ability of a dynamical system to produce changes (motion) in its own system state as well as changes in the system states of its surroundings. Thermodynamics is a physical branch of science that deals with laws governing energy flow from one body to another and energy transformations from one form to another. These energy flow laws are captured by the fundamental principles known as the first and second laws of thermodynamics. The first law of thermodynamics gives a precise formulation of the equivalence of heat and work and states that among all system transformations, the net system energy is conserved. Hence, energy cannot be created out of nothing and cannot be destroyed, merely transferred from one form to another. The law of conservation of energy is not a mathematical truth, but rather the consequence of an immeasurable culmination of observations over the chronicle of our civilization and is a fundamental *axiom* of the science of heat. The first law does not tell us whether any particular process can actually occur, that is, it does not restrict the ability to convert work into heat or heat into work, except that energy must be conserved in the process. The second law of thermodynamics asserts that while the system energy is always conserved, it will be degraded to a point where it cannot produce any useful work. Hence, it is impossible to extract work from heat without at the same time discarding some heat giving rise to a monotonically increasing quantity known as *entropy*. While energy describes the state of a dynamical system, entropy refers to changes in the *status quo* of the system and is a measure of molecular disorder and the amount of wasted energy in a dynamical (energy) transformation from one state (form) to another.

Since the specific motion of every molecule of a thermodynamic system is impossible to predict, a *macroscopic* model of the system is typically used with appropriate macroscopic states which include pressure, volume, temperature, internal energy, and entropy, among others. However, a thermodynamically consistent energy flow model should ensure that the system energy can be modelled by a diffusion (conservation) equation in the form of a *parabolic* partial differential equation. These systems are infinite-dimensional and hence finite-dimensional approximations are of very high order giving rise to large-scale dynamical systems. Since energy is a fundamental concept in the analysis of large-scale dynamical systems and heat (energy) is a fundamental concept of thermodynamics involving the capacity of hot bodies (more energetic subsystems) to produce work, thermodynamics is a theory of large-scale dynamical systems. High dimensional dynamical systems can arise from both macroscopic and *microscopic* points of view. Microscopic thermodynamic models can have the form of a distributed parameter model or a large-scale system model comprised of a large number of interconnected subsystems. In contrast to macroscopic models involving the evolution of global quantities (e.g., energy, temperature, entropy, etc.), microscopic models are based upon the modeling of local quantities that describe the atoms and molecules that make up the system, and their speeds, energies, masses, angular momenta, behavior during collisions, etc. The mathematical formulations based on these quantities form the basis of *statistical mechanics.* Since microscopic details are obscured on the macroscopic level, it is appropriate to view a microscopic model as an inherent model of uncertainty. However, for a thermodynamic system the macroscopic and microscopic quantities are related since they are simply different ways of describing the same phenomena. Thus, if the global macroscopic quantities can be expressed in terms of the local microscopic quantities, the laws of thermodynamics could be described in the language of statistical mechanics. This interweaving of the microscopic and macroscopic points of view lead to diffusion being a natural consequence of dimensionality and, hence, uncertainty on the microscopic level despite the fact that there is no uncertainty about the diffusion process per se.

In this research [31, 45, 71], we place thermodynamics on a system-theoretic foundation. Specifically, since thermodynamic models are concerned with energy flow among subsystems, we develop a nonlinear compartmental dynamical system model that is characterized by energy conservation laws capturing the exchange of energy between coupled macroscopic subsystems. Furthermore, using graph theoretic notions we state two thermodynamic axioms consistent with the zeroth and second laws of thermodynamics that ensure that our large-scale dynamical system model gives rise to a thermodynamically consistent energy flow model. Specifically, using a large-scale dynamical systems theory perspective for thermodynamics, we show that our compartmental dynamical system model leads to a precise formulation of the equivalence between work energy and heat in a large-scale dynamical system. Next, we give a deterministic definition of entropy for a large-scale dynamical system that is consistent with the classical thermodynamic definition of entropy and show that it satisfies a Clausius-type inequality leading to the law of entropy nonconservation. Furthermore, we introduce a *new* and dual notion to entropy; namely, *ectropy*, as a measure of the tendency of a large-scale dynamical system to do useful work and show that conservation of energy in an isolated thermodynamically consistent system necessarily leads to nonconservation of ectropy and entropy. Then, using the system ectropy as a Lyapunov function candidate we show that our thermodynamically consistent large-scale nonlinear dynamical system model possesses a continuum of equilibria and is *semistable*, that is, it has convergent subsystem energies to Lyapunov stable energy equilibria determined by the large-scale system initial subsystem energies. In addition, we show that the steady-state distribution of the large-scale system energies is uniform leading to system energy equipartitioning corresponding to a minimum ectropy and a maximum entropy equilibrium state. In Section 2.7 we show how we use this new thermodynamic system framework to analyze and design decentralized controllers for large-scale aerospace systems. The idea is to use two of the most fundamental laws of Nature (conservation of energy and nonconservation of entropy) to design stabilizing decentralized controllers (i.e., maximum entropy controllers) for large-scale aerospace systems that result in thermodynamically consistent closed-loop systems. In this case, stability of the closed-loop large-scale system would be guaranteed automatically in the face of system uncertainties.

2.3. Vector Dissipativity Theory for Large-Scale Hybrid Dynamical Systems

Recent technological demands have required the analysis and control design of increasingly complex, large-scale nonlinear dynamical systems. The complexity of modern controlled large-scale dynamical systems is further exacerbated by the use of hierarchial embedded control subsystems within the feedback control system, that is, abstract decision-making units performing logical checks that identity system mode operation and specify the continuous-variable subcontroller to be activated. Such systems typically possess a multiechelon hierarchical *hybrid* decentralized control architecture characterized by continuous-time dynamics at the lower levels of the hierarchy and discrete-time dynamics at the higher levels of the hierarchy. The lower-level units directly interact with the dynamical system to be controlled while the higher-level units receive information from the lower-level units as inputs and provide (possibly discrete) output commands which serve to coordinate and reconcile the (sometimes competing) actions of the lower-level units. The hierarchical controller organization reduces processor cost and controller complexity by breaking up the processing task into relatively small pieces and decomposing the fast and slow control functions. Typically, the higher-level units perform logical checks that determine system mode operation, while the lower-level units execute continuous-variable commands for a given system mode of operation.

In analyzing hybrid large-scale dynamical systems it is often desirable to treat the overall system as a collection of interconnected subsystems. The behavior of the composite hybrid large-scale system can then be predicted from the behaviors of the individual subsystems and their interconnections. The mathematical description of many of these systems can be characterized by impulsive differential equations. In particular, general hybrid dynamical systems involve an abstract axiomatic definition of a dynamical system involving left-continuous (or right-continuous) flows defined on a completely ordered time set as a mapping between vector spaces satisfying an appropriate set of axioms and include hybrid inputs and hybrid outputs that take their values in appropriate vector spaces. In contrast, impulsive dynamical systems are a subclass of hybrid dynamical systems and consist of three elements; namely, a continuous-time differential equation, which governs the motion of the dynamical system between impulsive events; a difference equation, which governs the way that the system states are instantaneously changed when an impulsive event occurs; and a criterion for determining when the states are to be reset.

As discussed in Section 2.1, an approach to analyzing large-scale dynamical systems was introduced by the pioneering work of Šiljak and involves the notion of *connective stability*. In particular, the large-scale dynamical system is decomposed into a collection of subsystems with local dynamics and uncertain interactions. Then, each subsystem is considered independently so that the stability of each subsystem is combined with the interconnection constraints to obtain a *vector Lyapunov function* for the composite large-scale dynamical system guaranteeing connective stability for the overall system. Vector Lyapunov functions were first introduced by Bellman and Matrosov and further developed in the literature, with exploiting their utility for analyzing large-scale systems. Extensions of vector Lyapunov function theory that include matrix-valued Lyapunov functions for stability analysis of large-scale dynamical systems appear in the monographs by Martynyuk. The use of vector Lyapunov functions in large-scale system analysis offers a very flexible framework since each component of the vector Lyapunov function can satisfy less rigid requirements as compared to a single scalar Lyapunov function. Weakening the hypothesis on the Lyapunov function enlarges the class of Lyapunov functions that can be used for analyzing the stability of large-scale dynamical systems. In particular, each component of a vector Lyapunov function need not be positive definite with a negative or even negative-semidefinite derivative. The time derivative of the vector Lyapunov function need only satisfy an element-by-element vector inequality involving a vector field of a certain comparison system.

In light of the fact that energy flow modeling arises naturally in large-scale dynamical systems and vector Lyapunov functions provide a powerful stability analysis framework for these systems, it seems natural that hybrid dissipativity theory, on the subsystem level, should play a key role in analyzing large-scale impulsive dynamical systems. Specifically, hybrid dissipativity theory provides a fundamental framework for the analysis and design of impulsive dynamical systems using an input-output description based on system energy[1] related considerations. The hybrid dissipation hypothesis on impulsive dynamical systems results in a fundamental constraint on their dynamic behavior wherein a dissipative impulsive dynamical system can only deliver a fraction of its energy to its surroundings and can only store a fraction of the work done to it. Such conservation laws are prevalent in large-scale impulsive dynamical systems such as aerospace systems, power systems, network systems, telecommunications systems, and transportation systems. Since these systems have numerous input-output properties related to conservation, dissipation, and transport of energy, extending hybrid dissipativity theory to capture conservation and dissipation notions on the subsystem level would provide a natural energy flow model for large-scale impulsive dynamical systems. Aggregating the dissipativity properties of each of the impulsive subsystems by appropriate storage functions and hybrid supply rates would allow us to study the dissipativity properties of the composite large-scale impulsive system using *vector storage functions* and *vector hybrid supply rates.* Furthermore, since vector Lyapunov functions can be viewed as generalizations of composite energy functions for all of the impulsive subsystems, a generalized notion of hybrid dissipativity; namely, *vector hybrid dissipativity,* with appropriate vector storage functions and vector hybrid supply rates, can be used to construct vector Lyapunov functions for nonlinear feedback large-scale impulsive systems by appropriately combining vector storage functions for the forward and feedback large-scale impulsive systems. Finally, as in classical dynamical system theory, vector dissipativity theory can play a fundamental role in addressing robustness, disturbance rejection, stability of feedback interconnections, and optimality for large-scale impulsive dynamical systems.

In this research [20], we develop vector dissipativity notions for large-scale nonlinear impulsive dynamical systems; a notion not previously considered in the literature. In particular, we introduce a generalized definition of dissipativity for large-scale nonlinear impulsive dynamical systems in terms of a *hybrid vector inequality* involving a vector hybrid supply rate, a vector storage function, and an essentially nonnegative, semistable dissipation matrix. Generalized notions of vector available storage and vector required supply are also defined and shown to be element-by-element ordered, nonnegative, and finite. On the impulsive subsys-

[1]Here the notion of energy refers to abstract energy for which a physical system energy interpretation is not necessary.

tem level, the proposed approach provides an energy flow balance over the continuous-time dynamics and the resetting events in terms of the stored subsystem energy, the supplied subsystem energy, the subsystem energy gained from all other subsystems independent of the subsystem coupling strengths, and the subsystem energy dissipated. Furthermore, for large-scale impulsive dynamical systems decomposed into interconnected impulsive subsystems, dissipativity of the composite impulsive system is shown to be determined from the dissipativity properties of the individual impulsive subsystems and the nature of the interconnections. In addition, we develop extended Kalman-Yakubovich-Popov conditions, in terms of the local impulsive subsystem dynamics and the interconnection constraints, for characterizing vector dissipativeness via vector storage functions for large-scale impulsive dynamical systems. Using the concepts of vector dissipativity and vector storage functions as candidate vector Lyapunov functions, we develop feedback interconnection stability results of large-scale impulsive nonlinear dynamical systems. General stability criteria are given for Lyapunov and asymptotic stability of feedback large-scale impulsive dynamical systems. In the case of vector quadratic supply rates involving net subsystem powers and input-output subsystem energies, these results provide a positivity and small gain theorem for large-scale impulsive systems predicated on vector Lyapunov functions.

2.4. Vector Dissipativity Theory for Discrete-Time Large-Scale Dynamical Systems

Since most physical processes evolve naturally in continuous-time, it is not surprising that the bulk of large-scale dynamical system theory has been developed for continuous-time systems. Nevertheless, it is the overwhelming trend to implement controllers digitally. Hence, in this research [13] we extend the notions of dissipativity theory to develop *vector dissipativity* notions for large-scale nonlinear discrete-time dynamical systems. In particular, we introduce a generalized definition of dissipativity for large-scale nonlinear discrete-time dynamical systems in terms of a *vector inequality* involving a *vector supply rate*, a *vector storage function*, and a nonnegative, semistable dissipation matrix. Generalized notions of vector available storage and vector required supply are also defined and shown to be element-by-element ordered, nonnegative, and finite. On the subsystem level, the proposed approach provides a discrete energy flow balance in terms of the stored subsystem energy, the supplied subsystem energy, the subsystem energy gained from all other subsystems independent of the subsystem coupling strengths, and the subsystem energy dissipated. Furthermore, for large-scale discrete-time dynamical systems decomposed into interconnected subsystems, dissipativity of the composite system is shown to be determined from the dissipativity properties of the individual subsystems and the nature of the interconnections. In particular, we develop extended Kalman-Yakubovich-Popov conditions, in terms of the local subsystem dynamics and the interconnection constraints, for characterizing vector dissipativeness via vector storage functions for large-scale discrete-time dynamical systems. Finally, using the concepts of vector dissipativity and vector storage functions as candidate vector Lyapunov functions, we develop feedback interconnection stability results of large-scale discrete-time nonlinear dynamical systems. General stability criteria are given for Lyapunov and asymptotic stability of feedback interconnections of large-scale discrete-time dynamical systems. In the case of vector quadratic supply rates involving net subsystem powers and input-output subsystem energies, these results provide a positivity and small gain theorem for large-scale discrete-time systems predicated on vector Lyapunov functions.

2.5. Thermodynamic Modeling for Discrete-Time Dynamical Systems

Thermodynamic principles have been repeatedly used in continuous-time dynamical system theory as well as information theory for developing models that capture the exchange of nonnegative quantities (e.g., mass and energy) between coupled subsystems. In particular, conservation laws (e.g., mass and energy) are used to capture the exchange of material between coupled macroscopic subsystems known as compartments. Each compartment is assumed to be kinetically homogeneous, that is, any material entering the compartment is instantaneously mixed with the material in the compartment. These models are known as *compartmental* models and are widespread in engineering systems as well as biological and ecological sciences. Even though the compartmental models developed in the literature are based on the first law of thermodynamics involving conservation of energy principles, they do not tell us whether any particular process can actually occur; that is, they do not address the second law of thermodynamics involving entropy notions in the energy flow between subsystems.

The goal of this research [29] is directed toward developing nonlinear discrete-time compartmental models that are consistent with thermodynamic principles. Specifically, since thermodynamic models are concerned with energy flow among subsystems, we develop a nonlinear compartmental dynamical system model that is characterized by energy conservation laws capturing the exchange of energy between coupled macroscopic subsystems. Furthermore, using graph theoretic notions we state three thermodynamic axioms consistent with the zeroth and second laws of thermodynamics that ensure that our large-scale dynamical system model gives rise to a thermodynamically consistent energy flow model. Specifically, using a large-scale dynamical systems theory perspective, we show that our compartmental dynamical system model leads to a precise formulation of the equivalence between work energy and heat in a large-scale dynamical system.

Next, we give a deterministic definition of entropy for a large-scale dynamical system that is consistent with the classical thermodynamic definition of entropy and show that it satisfies a Clausius-type inequality leading to the law of entropy nonconservation. Furthermore, we introduce a *new* and dual notion to entropy, namely, *ectropy*, as a measure of the tendency of a large-scale dynamical system to do useful work and grow more organized, and show that conservation of energy in an isolated thermodynamically consistent system necessarily leads to nonconservation of ectropy and entropy. Then, using the system ectropy as a Lyapunov function candidate we show that our thermodynamically consistent large-scale nonlinear dynamical system model possesses a continuum of equilibria and is *semistable*, that is, it has convergent subsystem energies to Lyapunov stable energy equilibria determined by the large-scale system initial subsystem energies. In addition, we show that the steady-state distribution of the large-scale system energies is uniform leading to system energy equipartitioning corresponding to a minimum ectropy and a maximum entropy equilibrium state. In the case where the subsystem energies are proportional to subsystem temperatures, we show that our dynamical system model leads to temperature equipartition wherein all the system energy is transferred into heat at a uniform temperature. Furthermore, we show that our system-theoretic definition of entropy and the newly proposed notion of ectropy are consistent with Boltzmann's kinetic theory of gases involving an n-body theory of ideal gases divided by diathermal walls. As in the case of continuous-time systems (see Section 2.7) this new thermodynamic system framework can be used to analyze and design decentralized controllers for discrete-time large-scale systems.

2.6. Stability Analysis and Control Design of Nonlinear Dynamical Systems via Vector Lyapunov Functions

One of the most basic issues in system theory is the stability of dynamical systems. The most complete contribution to the stability analysis of nonlinear dynamical systems is due to Lyapunov. Lyapunov's results, along with the Krasovskii-LaSalle invariance principle, provide a powerful framework for analyzing the stability of nonlinear dynamical systems. Lyapunov methods have also been used by control system designers to obtain stabilizing feedback controllers for nonlinear systems. In particular, for smooth feedback, Lyapunov-based methods were inspired by Jurdjevic and Quinn who give sufficient conditions for smooth stabilization based on the ability of constructing a Lyapunov function for the closed-loop system. More recently, Artstein introduced the notion of a control Lyapunov function whose existence guarantees a feedback control law which globally stabilizes a nonlinear dynamical system. In general, the feedback control law is not necessarily smooth, but can be guaranteed to be at least continuous at the origin in addition to being smooth everywhere else. Even though for certain classes of nonlinear dynamical systems a universal construction of a feedback stabilizer can be obtained using control Lyapunov functions, there does not exist a unified procedure for finding a Lyapunov function candidate that will stabilize the closed-loop system for general nonlinear systems.

In an attempt to simplify the construction of Lyapunov functions for the analysis and control design of nonlinear dynamical systems, several researchers have resorted to vector Lyapunov functions as an alternative to scalar Lyapunov functions. The use of vector Lyapunov functions in dynamical system theory offers a very flexible framework since each component of the vector Lyapunov function can satisfy less rigid requirements as compared to a single scalar Lyapunov function. Weakening the hypothesis on the Lyapunov function enlarges the class of Lyapunov functions that can be used for analyzing system stability. In particular, each component of a vector Lyapunov function need not be positive definite with a negative or even negative-semidefinite derivative. Alternatively, the time derivative of the vector Lyapunov function need only satisfy an element-by-element inequality involving a vector field of a certain comparison system. Since in this case the stability properties of the comparison system imply the stability properties of the dynamical system, the use of vector Lyapunov theory can significantly reduce the complexity (i.e., dimensionality) of the dynamical system being analyzed.

In this research [33], we extend the theory of vector Lyapunov functions in several directions. Specifically, we construct a generalized comparison system whose vector field can be a function of the comparison system states as well as the nonlinear dynamical system states. Next, using partial stability notions for the comparison system we provide sufficient conditions for stability of the nonlinear dynamical system. In addition, we present a convergence result reminiscent to the invariance principle that allows us to weaken the hypothesis on the comparison system while guaranteeing asymptotic stability of the nonlinear dynamical system via vector Lyapunov functions. Furthermore, we introduce the notion of a control vector Lyapunov function as a generalization of control Lyapunov functions and show that asymptotic stabilizability of a nonlinear dynamical system is equivalent to the existence of a control vector Lyapunov function. In addition, using control vector Lyapunov functions, we present a universal decentralized feedback stabilizer for a decentralized affine in the control nonlinear dynamical system with guaranteed gain and sector margins. Furthermore, we establish connections between vector dissipativity notions [16, 21] and inverse optimality of decentralized nonlinear regulators. These results are then used to develop decentralized controllers for large-scale dynamical systems with robustness guarantees against full modeling and input uncertainty.

2.7. Thermodynamic Stabilization via Energy Dissipating Hybrid Controllers

Energy is a concept that underlies our understanding of all physical phenomena and is a measure of the ability of a dynamical system to produce changes (motion) in its own system state as well as changes in the system states of its surroundings. In control engineering, dissipativity theory, which encompasses passivity theory, provides a fundamental framework for the analysis and control design of dynamical systems using an input-output system description based on system energy related considerations. The notion of energy here refers to abstract energy notions for which a physical system energy interpretation is not necessary. The dissipation hypothesis on dynamical systems results in a fundamental constraint on their dynamic behavior, wherein a dissipative dynamical system can only deliver a fraction of its energy to its surroundings and can only store a fraction of the work done to it. Thus, dissipativity theory provides a powerful framework for the analysis and control design of dynamical systems based on generalized energy considerations by exploiting the notion that numerous physical systems have certain input-output properties related to conservation, dissipation, and transport of energy. Such conservation laws are prevalent in dynamical systems such as aerospace systems, mechanical systems, fluid systems, electromechanical systems, electrical systems, combustion systems, structural vibration systems, biological systems, physiological systems, power systems, telecommunications systems, and economic systems, to cite but a few examples.

Energy-based control for Euler-Lagrange dynamical systems and Hamiltonian dynamical systems based on passivity notions has received considerable attention in the literature. This controller design technique achieves system stabilization by shaping the energy of the closed-loop system which involves the physical system energy and the controller emulated energy. Specifically, *energy shaping* is achieved by modifying the system potential energy in such a way so that the shaped potential energy function for the closed-loop system possesses a unique global minimum at a desired equilibrium point. Next, damping is *injected* via feedback control modifying the system dissipation to guarantee asymptotic stability of the closed-loop system. A central feature of this energy-based stabilization approach is that the Lagrangian system form is preserved at the closed-loop system level. Furthermore, the control action has a clear physical energy interpretation, wherein the total energy of the closed-loop Euler-Lagrange system corresponds to the difference between the physical system energy and the emulated energy supplied by the controller.

More recently, a passivity-based control framework for port-controlled Hamiltonian systems is established in the literature. Specifically, control researchers have developed a controller design methodology that achieves stabilization via system passivation. In particular, the interconnection and damping matrix functions of the port-controlled Hamiltonian system are shaped so that the physical (Hamiltonian) system structure is preserved at the closed-loop level, and the closed-loop energy function is equal to the difference between the physical energy of the system and the energy supplied by the controller. Since the Hamiltonian structure is preserved at the closed-loop level, the passivity-based controller is *robust* with respect to unmodeled passive dynamics. Furthermore, passivity-based control architectures are extremely appealing since the control action has a clear *physical* energy interpretation which can considerably simplify controller implementation.

In this research [34,36,54], we develop a novel energy dissipating hybrid control framework for Lagrangian, port-controlled Hamiltonian, lossless, and dissipative dynamical systems. These dynamical systems cover a very broad spectrum of applications including aerospace, mechanical, electrical, electromechanical, structural, biological, and power systems. The fixed-order, energy-based hybrid controller is a hybrid controller that emulates an approximately lossless dynamical system and exploits the feature that the states of the dynamic controller may be reset to enhance the overall energy dissipation in the closed-loop system. An important feature of the hybrid controller is that its structure can be associated with an energy function. In a mechanical Euler-Lagrange system, positions typically correspond to elastic deformations, which contribute to the potential energy of the system, whereas velocities typically correspond to momenta, which contribute to the kinetic energy of the system. On the other hand, while our energy-based hybrid controller has dynamical states that emulate the motion of a physical lossless system, these states only "exist" as numerical representations inside the processor. Consequently, while one can associate an *emulated energy* with these states, this energy is merely a mathematical construct and does not correspond to any physical form of energy.

The concept of an energy-based hybrid controller can be viewed as a feedback control technique that exploits the coupling between a physical dynamical system and an energy-based controller to efficiently remove energy from the physical system. Specifically, if a dissipative or lossless plant is at high energy level, and a lossless feedback controller at a low energy level is attached to it, then energy will generally tend to flow from the plant into the controller, decreasing the plant energy and increasing the controller energy. Of course, emulated energy, and not physical energy, is accumulated by the controller. Conversely, if the attached controller is at a high energy level and a plant is at a low energy level, then energy can flow from the controller to the plant, since a controller can generate real, physical energy to effect the required energy flow. Hence, if and when the controller states coincide with a high emulated energy level, then we can *reset* these states to remove the emulated energy so that the emulated energy is not returned to the plant. In this case, the overall closed-loop system consisting of the plant and the controller possesses discontinuous flows since it combines logical switchings with continuous dynamics, leading to impulsive differential equations.

Impulsive dynamical systems can be viewed as a subclass of hybrid systems and consist of three elements; namely, a continuous-time differential equation, which governs the motion of the dynamical system between impulsive or resetting events; a difference equation, which governs the way the system states are instantaneously changed when a resetting event occurs; and a criterion for determining when the states of the system are to be reset. As discussed in [54], energy-based hybrid controllers can involve two distinct forms for the resetting criterion, or resetting set. Specifically, the resetting set can be defined by a prescribed periodic sequence of times which are independent of the states of the closed-loop system. These controllers are thus called *time-dependent hybrid controllers.* Alternatively, the resetting set can be defined by a region in the state space that is independent of time. Here, the resetting action guarantees that the plant energy is strictly decreasing across resetting events. These controllers are called *state-dependent hybrid controllers.*

In this research, a novel class of fixed-order, energy-based hybrid controllers is developed as a means for achieving enhanced energy dissipation in Euler-Lagrange, port-controlled Hamiltonian, and lossless dynamical systems. These dynamic controllers combine a logical switching architecture with continuous dynamics to guarantee that the system plant energy is strictly decreasing across switchings. In addition, we construct hybrid dynamic controllers that guarantee that the closed-loop system is consistent with basic thermodynamic principles. In particular, the existence of an entropy function for the closed-loop system is established that satisfies a hybrid Clausius-type inequality. Special cases of energy-based hybrid controllers involving state-dependent switching are described, and the framework is applied to large-scale aerospace system models. The overall framework demonstrates that energy-based hybrid resetting controllers provide an extremely efficient mechanism for dissipating energy in large-scale systems (See Figures 1 and 2).

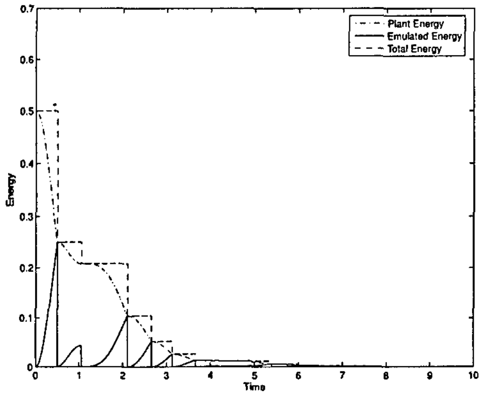

Figure 1: This plot shows the time history of the energy components of the plant, emulated controller energy, and total energy for a nonlinear large-scale Lienard system controlled by a hybrid thermodynamic controller.

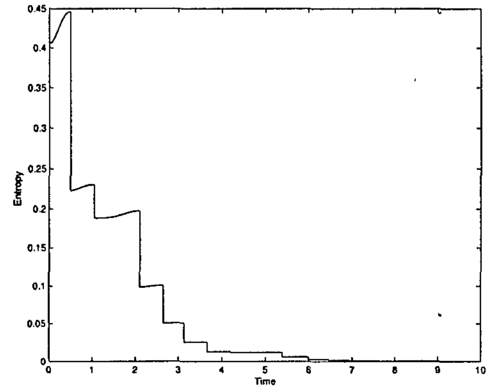

Figure 2: This plot shows the closed-loop system entropy as a function of time. Note that the entropy of the closed-loop system strictly increases between resetting events.

2.8. Hybrid Adaptive Control for Nonlinear Uncertain Impulsive Dynamical Systems

Modern complex engineering systems involve multiple modes of operation placing stringent demands on controller design and implementation of increasing complexity. Such systems typically possess a multiechelon hierarchical *hybrid* control architecture characterized by continuous-time dynamics at the lower levels of the hierarchy and discrete-time dynamics at the higher levels of the hierarchy. The lower-level units directly interact with the dynamical system to be controlled while the higher-level units receive information from the lower-level units as inputs and provide (possibly discrete) output commands which serve to coordinate and reconcile the (sometimes competing) actions of the lower-level units. The hierarchical controller organization reduces processor cost and controller complexity by breaking up the processing task into relatively small pieces and decomposing the fast and slow control functions. Typically, the higher-level units perform logical checks that determine system mode operation, while the lower-level units execute continuous-variable commands for a given system mode of operation. The mathematical description of many of these systems can be characterized by impulsive differential equations.

The ability of developing a hierarchical nonlinear integrated hybrid control-system design methodology for robust, high performance controllers satisfying multiple design criteria and real-world hardware constraints is imperative in light of the increasingly complex nature of dynamical systems requiring controls such as advanced high performance tactical fighter aircraft, variable-cycle gas turbine engines, biological and physiological systems, sampleddata systems, discrete-event systems, intelligent vehicle/highway systems, and flight control systems, to cite but a few examples. The inherent severe nonlinearities and uncertainties of these systems and the increasingly stringent performance requirements required for controlling such modern complex embedded systems necessitates the development of hybrid adaptive nonlinear control methodologies.

Even though adaptive control algorithms have been extensively developed in the literature for both continuous-time and discrete-time systems, hybrid adaptive control algorithms for hybrid dynamical systems are nonexistent. In this research [27], we develop a direct hybrid adaptive control framework for nonlinear uncertain impulsive dynamical systems. In particular, a Lyapunov-based hybrid adaptive control framework is developed that guarantees partial *asymptotic stability* of the closed-loop hybrid system, that is, asymptotic stability with respect to part of the closed-loop system states associated with the hybrid plant dynamics. Furthermore, the remainder of the state associated with the adaptive controller gains is shown to be Lyapunov stable. Next, using the hybrid invariance principle developed by the Principal Investigator and his coworkers, we relax several of the conditions needed for guaranteeing partial asymptotic stabilization to develop an alternative less restrictive hybrid adaptive control framework that guarantees *attraction* of the closed-loop system states associated with the hybrid plant dynamics. In this case, the remainder of the state associated with the hybrid adaptive controller gains is shown to be bounded. In the case where the nonlinear hybrid system is represented in a *hybrid normal form*, the nonlinear hybrid adaptive controllers are constructed *without* requiring knowledge of the hybrid system dynamics.

2.9. Neural Network Adaptive Control for Nonlinear Nonnegative Dynamical Systems

One of the primary reasons for the large interest in neural networks is their capability to approximate a large class of continuous nonlinear maps from the collective action of very simple, autonomous processing units interconnected in simple ways. Neural networks have also attracted attention due to their inherently parallel and highly redundant processing architecture that makes it possible to develop parallel weight update laws. This parallelism makes it possible to effectively update a neural network on line. These properties make neural networks a viable paradigm for adaptive system identification and control of complex highly uncertain dynamical systems, and as a consequence the use of neural networks for identification and control has become an active area of research.

Modern complex engineering systems as well as biological and physiological systems are highly interconnected and mutually interdependent, both physically and through a multitude of information and communication networks. By properly formulating these systems in terms of subsystem interaction and energy/mass transfer, the dynamical models of many of these systems can be derived from mass, energy, and information balance considerations that involve dynamic states whose values are nonnegative. Hence, it follows from physical considerations that the state trajectory of such systems remains in the nonnegative orthant of the state space for nonnegative initial conditions. Such systems are commonly referred to as *nonnegative dynamical systems* in the literature. A subclass of nonnegative dynamical systems are *compartmental systems.* Compartmental systems involve dynamical models that are characterized by conservation laws (e.g., mass and energy) capturing the exchange of material between coupled macroscopic subsystems known as compartments. Each compartment is assumed to be kinetically homogeneous, that is, any material entering the compartment is instantaneously mixed with the material of the compartment. The range of application of nonnegative systems and compartmental systems is quite large and includes biological, ecological, and chemical systems. Due to the severe complexities, nonlinearities, and uncertainties inherent in these systems, neural networks provide an ideal framework for on-line adaptive control because of their parallel processing flexibility and adaptability.

In this research [24, 25], we develop a full-state feedback neural adaptive control framework for set-point regulation of nonlinear uncertain nonnegative and compartmental systems. Nonzero set-point regulation for nonnegative dynamical systems is a key design requirement since stabilization of nonnegative systems naturally deals with equilibrium points in the interior of the nonnegative orthant. The proposed framework is Lyapunov-based and guarantees ultimate boundedness of the error signals corresponding to the physical system states as well as the neural network weighting gains. The neuro adaptive controllers are constructed *without* requiring knowledge of the system dynamics while guaranteeing that the physical system states remain in the nonnegative orthant of the state space. The proposed neuro control architecture is modular in the sense that if a nominal linear design model is available, the neuro adaptive controller can be augmented to the nominal design to account for system nonlinearities and system uncertainty. Furthermore, since in certain applications of nonnegative and compartmental systems (e.g., pharmacological systems for active drug administration) control (source) inputs as well as the system states need to be nonnegative, we also develop neuro adaptive controllers that guarantee the control signal as well as the physical system states remain nonnegative for nonnegative initial conditions. We note that neuro adaptive controllers for nonnegative dynamical systems have not been addressed in the literature. Finally, the proposed neuro adaptive control framework is used to regulate the temperature of a continuously stirred tank reactor involving exothermic irreversible reactions.

2.10. Adaptive Control for General Anesthesia and Intensive Care Unit Sedation

Even though advanced robust and adaptive control methodologies have been (and are being) extensively developed for highly complex engineering systems, modern active control technology has received far less consideration in medical systems. The main reason for this state of affairs is the steep barriers to communication between mathematics/control engineering and medicine. However, this is slowly changing and there is no doubt that control-system technology has a great deal to offer medicine. For example, critical care patients, whether undergoing surgery or recovering in intensive care units, require drug administration to regulate key physiological (state) variables (e.g., blood pressure, temperature, glucose, degree of consciousness, etc.) within desired levels. The rate of infusion of each administered drug is *critical*, requiring constant monitoring and frequent adjustments. Open-loop control (manual control) by clinical personnel can be very tedious, imprecise, time consuming, and often of poor quality. Hence, the need for active control (closed-loop control) in medical systems is severe; with the potential in improving the quality of medical care as well as curtailing the increasing cost of health care.

The complex highly uncertain and hostile environment of surgery places stringent performance requirements for closed-loop set-point regulation of physiological variables. For example, during cardiac surgery, blood pressure control is vital and is subject to numerous highly uncertain exogenous disturbances. Vasoactive and cardioactive drugs are administered resulting in large disturbance oscillations to the system (patient). The arterial line may be flushed and blood may be drawn, corrupting sensor blood pressure measurements. Low anesthetic levels may cause the patient to react to painful stimuli, thereby changing system (patient) response characteristics. The flow rate of vasodilator drug infusion may fluctuate causing transient changes in the infusion delay time. Hemorrhage, patient position changes, cooling and warming of the patient, and changes in anesthesia levels will also effect system (patient) response characteristics.

In light of the complex and highly uncertain nature of system (patient) response characteristics under surgery requiring controls, it is not surprising that reliable system models for many high performance drug delivery systems are unavailable. In the face of such high levels of system uncertainty, robust controllers may unnecessarily sacrifice system performance whereas adaptive controllers are clearly appropriate since they can tolerate far greater system uncertainty levels to improve system performance. In contrast to fixed-gain robust controllers, which maintain specified constants within the feedback control law to *sustain* robust performance, adaptive controllers directly or indirectly adjust feedback gains to maintain closed-loop stability and *improve* performance in the face of system uncertainties. Specifically, indirect adaptive controllers utilize parameter update laws to identify unknown system parameters and adjust feedback gains to account for system variation, while direct adaptive controllers directly adjust the controller gains in response to system variations.

In this research [26], we developed a direct adaptive control framework for adaptive set-point regulation for uncertain nonnegative and compartmental systems. As noted in Section 2.9, nonnegative and compartmental dynamical systems are composed of homogeneous interconnected subsystems (or compartments) which exchange variable nonnegative quantities of material with conservation laws describing transfer, accumulation, and outflows between the compartments and the environment. Nonnegative and compartmental models thus play a key role in understanding many processes in biological and medical sciences. Using nonnegative and compartmental model structures, a Lyapunov-based direct adaptive control framework is developed that guarantees partial asymptotic set-point stability of the closed-loop system. In particular, adaptive controllers are constructed *without* requiring knowledge of the system dynamics while providing a nonnegative control (source) input for robust stabilization with respect to the nonnegative orthant. Modeling uncertainty in nonnegative and compartmental systems may arise in the system transfer coefficients due to patient gender, weight, pre-existing disease, age, and concomitant medication. Furthermore, in certain applications of nonnegative and compartmental systems such as biological systems, population dynamics, and ecological systems involving positive and negative inflows, the nonnegativity constraint on the control input is not natural. In this case, we also develop adaptive controllers that do not place any restriction on the sign of the control signal while guaranteeing that the physical system states remain in the nonnegative orthant of the state space. Finally, the proposed approach was used to control the infusion of the anesthetic drug propofol for maintaining a desired constant level of depth of anesthesia for noncardiac surgery (see Figures 3 and 4).

2.11. Neural Network Adaptive Control for Intensive Care Unit Sedation and Intraoperative Anesthesia

Control engineering has impacted almost every aspect of modern life, with applications ranging from relatively simple systems, such as thermostats and automotive cruise control, to highly complex systems, such as advanced tactical fighter aircraft and variable-cycle gas turbine aeroengines. Control technology has also had an impact on modern medicine in areas such as robotic surgery, electrophysiological systems (pacemakers and automatic implantable defibrillators), life support (ventilators, artificial hearts), and image-guided therapy

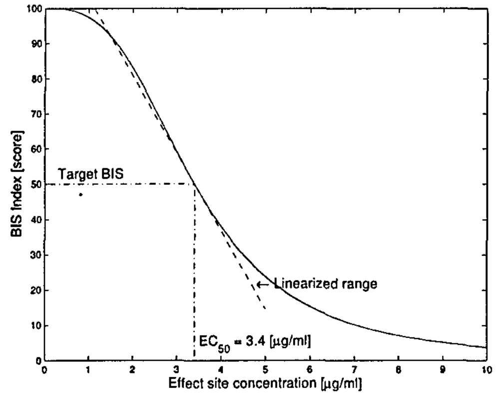

Figure 3: Bispectral (BIS) Index (electroencephalogram (EEG) indicator) versus effect site (brain) concentration. BIS index values of 0 and 100 correspond, respectively, to an isoelectric EEG signal and an EEG signal of a fully conscious patient; while the range between 40 to 60 indicates a moderate hypnotic state.

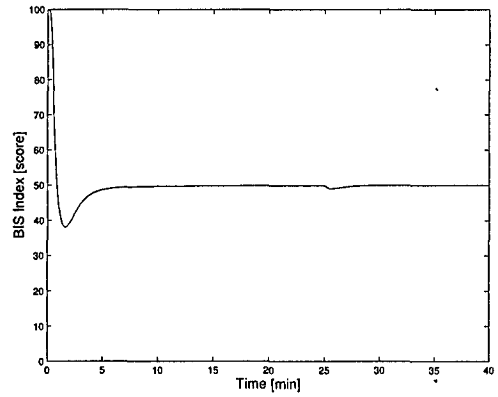

Figure 4: BIS Index versus time achieved by the proposed adaptive controller. The proposed adaptive controller does not require knowledge of the system parameters nor the BIS Index parameters.

and surgery. However, there remain barriers to the application of modern control theory and technology to medicine. These barriers include system uncertainties, inherent to biology, that limit mathematical modeling and the ability to apply many of the tools of modern control technology. An additional impediment is the relatively limited communication between control engineers and the medical community. One area of medicine most suited for applications of control technology is clinical pharmacology in which mathematical modeling has had a predominant role. This discipline includes *pharmacokinetics*, the relationship between drug dose and the resultant tissue concentrations as a function of time, and *pharmacodynamics*, the relationship between tissue concentration and drug effect. The mathematical foundation for pharmacokinetic and pharmacodynamic modeling is nonnegative and compartmental dynamical systems theory and so it is easy to see why control theory and technology may have much to offer clinical pharmacology.

It has long been appreciated that if one can identify a physiological variable that quantifies therapeutic drug effect and measure it continuously in real-time, it should be possible to utilize feedback (closed-loop) control, implemented with a computer, to maintain this variable, and hence the drug effect, at the desired value. By their very nature, cardiovascular and central nervous functions are critical in the acute care environment, such as the operating room or the intensive care unit, and hence mature technologies have evolved for their quantitative assessment. For this reason the primary application of closed-loop control of drug administration has been to hemodynamic management and, more recently, to control of levels of consciousness. As an example of the former application, the technology for the continuous measurement of blood pressure has been available for some time and systems have been developed to maintain blood pressure at the desired value in the operating room and intensive care unit.

The primary interest of our research has been in closed-loop control of the level of consciousness. While there is direct application of this research to the clinical task of operating room anesthesia, an application with potentially more impact is closed-loop control of level of consciousness of patients in intensive care units (ICU). Mechanical ventilation is uncomfortable and causes anxiety in the patient. Appropriate sedation of mechanically ventilated ICU patients is very challenging. The common clinical scenario is a patient who is either under sedated and "fighting the ventilator" or is over sedated, with concomitant sequelae such as hypotension or prolonged emergence from sedation when it is deemed appropriate to begin weaning the patient from the ventilator. We can envision a future in which infusion pumps contain a small computer chip that allow the ICU nurse to connect the patient to some monitor of level of consciousness, feed the signal into the chip, which then drives the pump to titrate intravenous hypnotic drugs to the appropriate level of sedation. Given the shortage of experienced ICU nurses, we believe this would be a significant advance, allowing clinicians to focus on tasks other than titrating sedation.

In this research [32,48], we extend the results to nonnegative and compartmental dynamical systems with applications to the specific problem of automated anesthesia. Specifically, we develop an output feedback neural network adaptive controller that operates over a tapped delay line of available input and output measurements. The neuro adaptive laws for the neural network weights are constructed using a linear observer for the nominal normal form system error dynamics. The approach is applicable to a general class of nonlinear nonnegative dynamical systems without imposing a strict positive real requirement on the transfer function of the linear error normal form dynamics. Furthermore, since in pharmacological applications involving active drug administration control inputs as well as the system states need to be nonnegative, the proposed neuro adaptive output feedback controller also guarantees that the control signal as well as the physiological system states remain nonnegative. We emphasize that the proposed framework addresses adaptive *output feedback* controllers for nonlinear nonnegative and compartmental systems with *unmodeled dynamics* of *unknown dimension* while guaranteing ultimate boundedness of the error signals corresponding to the physical system states as well as the neural network weighting gains. Output feedback controllers are crucial in clinical pharmacology since key physiological (state) variables cannot be measured in practice or in real time.

2.12. Adaptive Control of Mammillary Drug Delivery Systems with Actuator Amplitude Constraints and System Time Delays

Compartmental models play a key role in the understanding of many processes in biological and medical sciences. In many compartmental system models, transfers between compartments are assumed to be instantaneous, that is, the model does not account for material in transit. Even though this is a valid assumption for certain biological and physiological systems, it is not true in general; especially in pharmacokinetic and pharmacodynamic models. For example, if a bolus (impulsive) dose of drug is injected and we seek its concentration level in the extracellular and intercellular space of some organ, a time lag exists before it is detected in that organ. In this case, assuming instantaneous mass transfer between compartments will yield erroneous models. Although mixing times can be modeled by including additional compartments in series, even this model assumes instantaneous mixing in the initial compartment. To accurately describe the distribution of pharmacological agents in the human body, it is necessary to include in any mathematical compartmental pharmacokinetic model information of the past system states. In this case, the state of the system at any given time involves a *piece of trajectories* in the space of continuous functions defined on an interval in the nonnegative orthant. This of course leads to (infinite-dimensional) delay dynamical systems.

Since compartmental models provide a broad framework for biological and physiological systems, including clinical pharmacology, they are well suited for developing models for closed-loop control of drug administration. However, given the significant magnitude of intrapatient and interpatient variability, and the fact that an individual patient's drug sensitivity varies with time, adaptive control for active drug administration is clearly essential. In recent research [26], we developed an adaptive control algorithm using the electroencephalogram (EEG) as an objective, quantitative measure of consciousness for closed-loop control of anesthesia. An implicit assumption inherent in [26] is that the control law is implemented without any regard to actuator amplitude and rate saturation constraints. Of course, any electromechanical control actuation device (syringe pump) is subject to amplitude and/or rate constraints leading to saturation nonlinearities enforcing limitations on control amplitude and control rates. More importantly, in pharmacological applications, drug infusion rates can vary from patient to patient, and, to avoid overdosing, it is vital that the infusion rate does not exceed the patient-specific threshold values. As a consequence, control constraints, that is, infusion pump rate constraints, need to be accounted for in drug delivery systems.

In this research [30], we extend the results of [26] to the case of compartmental dynamical systems with unknown system time delays and control amplitude constraints. Specifically, we develop a Lyapunov-Krasovskii-based direct adaptive control framework for guaranteeing set-point regulation for linear uncertain compartmental dynamical systems with unknown time delay and control amplitude constraints. The specific focus of [30] is on pharmacokinetic models and their applications to drug delivery systems. Since the most common pharmacokinetic models are linear and *mammillary*, that is, models comprised of a *central compartment* from which there is outflow from the system and which exchanges material reversibly with one or more *peripheral compartments*, we develop direct adaptive controllers for mammillary systems. Finally, we numerically demonstrate the framework on a drug delivery model for general anesthesia that involves system time delays as well as control infusion rate constraints.

2.13. Optimal Fixed-Structure Control for Nonnegative Dynamical Systems

In this research [10], we develop optimal output feedback controllers for set-point regulation of linear nonnegative and compartmental dynamical systems. In particular, we extend the optimal fixed-structure control framework to develop optimal output feedback controllers that guarantee that the trajectories of the closed-loop plant system states remain in the nonnegative orthant of the state space for nonnegative initial conditions. The proposed optimal fixed-structure control framework is a *constrained* optimal control methodology that does not seek to optimize a performance measure per se, but rather seeks to optimize performance within a class of fixed-structure controllers satisfying internal controller constraints that guarantee the nonnegativity of the closed-loop plant system states. Furthermore, since unconstrained optimal controllers are globally optimal but may not guarantee nonnegativity of the closed-loop plant system states, we additionally characterize domains of attraction contained in the nonnegative orthant for unconstrained optimal output feedback controllers that guarantee nonnegativity of the closed-loop plant system trajectories. Specifically, domains of attraction contained in the nonnegative orthant for optimal output feedback controllers are computed using closed and open Lyapunov level surfaces. It is also shown that the domains of attraction predicated on open Lyapunov level surfaces provide a considerably improved region of asymptotic stability in the nonnegative orthant as compared to regions of attraction given by closed Lyapunov level surfaces.

2.14. Neural Network Adaptive Control for Nonlinear Uncertain Dynamical Systems with Asymptotic Stability Guarantees

Unlike adaptive controllers which guarantee asymptotic stability of the closed-loop system states associated with the system plant states, standard neural network adaptive controllers guarantee *ultimate boundedness* of the closed-loop system states. This fundamental difference between adaptive control and neuro adaptive control can be traced back to the modeling and treatment of the system uncertainties. In particular, adaptive control is based on *constant, linearly parameterized* system uncertainty models of a known structure but unknown variation, while neuro adaptive control is based on the universal function approximation property, wherein any continuous system uncertainty can be *approximated* arbitrarily closely on a compact set using a neural network with appropriate weights. This system uncertainty parametrization makes it impossible to construct a system Lyapunov function whose time derivative along the closed-loop system trajectories is guaranteed to be negative definite. Instead, the Lyapunov derivative can only be shown to be negative on a sublevel set of the system Lyapunov function. This shows that, in this sublevel set, the Lyapunov function will decrease monotonically until the system trajectories enter a compact set containing the desired system equilibrium point, and thus, guaranteeing ultimate boundedness. This analysis is often conservative since standard Lyapunov-like theorems used to show ultimate boundedness of the closed-loop system states provide only sufficient conditions, while neural network controllers often achieve plant state convergence to a desired equilibrium point.

In this research [52], we develop a neuro adaptive control framework for a class of nonlinear uncertain dynamical systems which guarantees asymptotic stability of the closed-loop system states associated with the system plant states, as well as boundedness of the neural network weighting gains. The proposed framework is Lyapunov-based and guarantees partial asymptotic stability of the closed-loop system, that is, Lyapunov stability of the overall closed-loop system states and convergence of the plant states. The neuro adaptive controllers are constructed without requiring explicit knowledge of the system dynamics other than the assumption that the plant dynamics are continuously differentiable and that the approximation error of uncertain system nonlinearities lie in a small gain-type norm bounded conic sector. Furthermore, the proposed neuro control architecture is modular in the sense that if a nominal linear design model is available, then the neuro adaptive controller can be augmented to the nominal design to account for system nonlinearities and system uncertainty.

2.15. On State Equipartitioning and Semistability in Network Dynamical Systems with Arbitrary Time-Delays

Nonnegative and compartmental models are also widespread in agreement problems in networks with directed graphs and switching topologies. Specifically, distributed decision-making for coordination of networks of dynamic agents involving information flow can be naturally captured by compartmental models. These dynamical network systems cover a very broad spectrum of applications including cooperative control of unmanned air vehicles, distributed sensor networks, swarms of air and space vehicle formations, and congestion control in communication networks. In many applications involving multiagent systems, groups of agents are required to agree on certain quantities of interest. In particular, it is important to develop consensus protocols for networks of dynamic agents with directed information flow, switching network topologies, and possible system time-delays. In this research [50], we use compartmental dynamical system models to characterize dynamic algorithms for linear and nonlinear networks of dynamic agents in the presence of inter-agent communication delays that possess a continuum of *semistable* equilibria, that is, protocol algorithms that guarantee convergence to Lyapunov stable equilibria. In addition, we show that the steady-state distribution of the dynamic network is uniform, leading to system state equipartitioning or consensus. These results extend the results in the literature on consensus protocols for linear balanced networks to linear and nonlinear unbalanced networks with switching topologies and time-delays.

2.16. Subspace Identification of Stable Nonnegative and Compartmental Dynamical Systems via Constrained Optimization

While compartmental systems have wide applicability in biology and medicine, their use in the specific field of pharmacokinetics is particularly noteworthy. The goal of pharmacokinetic analysis often is to characterize the kinetics of drug disposition in terms of the parameters of a compartmental model. This is accomplished by postulating a model, collecting experimental data (typically drug concentrations in blood as a function of time), and then using statistical analysis to estimate parameter values which best describe the data. There are numerous sources of noise in the data, from assay error to human recording error. Because of model approximation and noise, there is always an offset between the concentration predicted by the model and the observed data, namely, the prediction error. One method for estimating pharmacokinetic parameters is maximum likelihood. This approach assumes a statistical distribution for the prediction error and then determines the parameter values that maximize the likelihood of the observed results.

There are two distinct approaches to estimating mean pharmacokinetic parameters for a population of patients. In the first approach, models are fitted to data from individual patients, and the pharmacokinetic parameters are then averaged (*two-stage analysis*) to provide a measure of the pharmacokinetic parameters for the population. The second approach is to pool the data from individual patients, called *mixed-effects modeling*; in this situation the prediction error is determined by the stochastic noise of the experiment and by the fact that *different patients have different pharmacokinetic parameters.* The statistical model used to account for the discrepancy between observed and predicted concentrations must take into consideration not only variability between observed and predicted concentrations within the same patient (*intrapatient* variability), but also variability between patients (*interpatient* variability). Most commonly, it is assumed that the interpatient variability of pharmacokinetic parameters conforms to a log-normal distribution. This method of analysis estimates the mean structural pharmacokinetic parameters as well as the statistical variability of these elements in the population.

While system *identifiability* for nonnegative and compartmental systems has been widely explored in the literature, the system *identification* problem for these class of systems has received less attention. System identification refers to the overall problem of determining system structure as well as system parameter values from input-output data, whereas system identifiability refers to the narrower problem of existence and uniqueness of solutions. Namely, system identifiability concerns whether or not there is enough information in the observations to uniquely determine system parameters.

In this research [53], we develop a system identification framework for stable nonnegative and compartmental dynamical systems within the context of subspace identification. Subspace identification methods differ from classical least squares identification methods in that estimates of a state sequence is used to provide estimates of the system parameters. Our multivariable framework is based on a constrained weighted least squares optimization problem involving a stability constraint on the plant system matrix as well as a nonnegativity constraint on the system matrices. The resulting constrained optimization problem is cast as a convex linear programming problem over symmetric cones involving a weighted cost function with mixed equality, inequality, quadratic, and nonnegative-definite constraints. Our approach builds on the subspace identification technique presented in the literature guaranteeing system stability to address stable nonnegative and compartmental dynamical systems. Finally, to solve the resulting convex optimization problem, we apply the SeDuMi MATLAB code to the constrained least squares problem.

2.17. The Structured Phase Margin for Stability Analysis of Linear Systems with Phase and Time Delay Uncertainties

Phase information has largely been neglected in robust control theory, but is essential for maximizing achievable performance in controlling uncertain dynamical systems. Phase information, here, refers to the characterization of the phase of the modeling uncertainty in the frequency domain. The analysis and synthesis of robust feedback controllers entails a fundamental distinction between parametric and nonparametric uncertainty. Parametric uncertainty refers to plant uncertainty that is modeled as constant real parameters, whereas nonparametric uncertainty refers to uncertain transfer function gains that may be modeled as complex frequency-dependent quantities. Real parametric uncertainty in the time domain provides phase information in the frequency domain.

The distinction between parametric and nonparametric uncertainty is critical to the achievable performance of feedback control systems. This distinction can be illustrated by considering the central result of feedback control theory, namely, the small gain theorem, which guarantees robust stability by requiring that the loop gain (including desired weighting functions for loop shaping) be less than unity at all frequencies. The small gain theorem, however, does not make use of phase information in guaranteeing stability. In fact, the small gain theorem allows the loop transfer function to possess arbitrary phase at all frequencies, although in many applications at least some knowledge of phase is available. Thus, small gain techniques such as H_∞ theory are generally conservative when phase information is available. More generally, since $|e^{\jmath\phi}| = 1$ regardless of the phase angle ϕ, it can be expected that any robustness theory based upon norm bounds will suffer from the same shortcoming. Of course, every real parameter can be viewed as a complex parameter with phase $\phi = 0°$ or $\phi = 180°$.

To some extent, phase information is accounted for by means of positivity theory. In this theory, a positive real plant and a strictly positive real uncertainty are both assumed to have phase less than 90° so that the loop transfer function has less than 180° of phase shift, hence guaranteeing robust stability in spite of gain uncertainty. Both gain and phase properties can be simultaneously accounted for by means of the circle criterion which yields the small gain and positivity theorems as special cases. It is important to note, however, that positivity theory and the circle criterion can be obtained from small gain conditions by means of suitable transformations, and hence, are equivalent results from a mathematical point of view.

The ability to address block-structured gain and phase uncertainty is essential for reducing conservatism in the analysis and synthesis of control systems involving robust stability and performance objectives. Accordingly, the structured singular value provides a generalization of the spectral (maximum singular value) norm to permit small-gain type analysis of systems involving block-structured complex, real, and mixed uncertainty. Even though the structured singular value guarantees robust stability by means of bounds involving frequency-dependent scales and multipliers which account for the structure of the uncertainty as well as its real or complex nature, it does not directly capture phase uncertainty information.

Phase information for uncertain dynamical systems has been studied by a significant number of researchers. Concepts such as principal phases, multivariable phase margin, phase spread, phase envelope, phase matching, phase-sensitive structured singular value, and plant uncertainty templates are notable contributions. Principal phases are defined to be the phase angles associated with the eigenvalues of the unitary part of the polar decomposition of a complex matrix. Exploiting transfer function phase information, a small phase theorem has been developed that provides less conservative stability results than the small gain theorem. An alternative approach to capturing phase uncertainty is given in terms of the numerical range. In particular, the numerical range provides both gain and phase information, and hence, can be used to guarantee robust stability with respect to system uncertainties having phase-dependent gain variation. Phase-sensitive structured singular value results are obtained in the literature that allow the incorporation of phase information with multiple-block uncertainty. An additional class of results involving phase matching for addressing system phase uncertainty is also reported in the literature. Here, the goal is to obtain a reduced-order model of a power spectral density by approximating the phase of the spectral factor. An input-output description of system uncertainty can also be characterized in terms of gain and phase envelopes. Finally, gain and phase information is addressed by Quantitative Feedback Theory in the form of frequency domain uncertainty templates which account for both structured and unstructured uncertainty.

Phase information is critical in capturing system time delays which play an important role in modern engineering systems. In particular, many complex engineering network systems involve power transfers between interconnected system components that are not instantaneous, and hence, realistic models for capturing the dynamics of such systems should account for information in transit. Such models lead to delay dynamical systems. Time-delay dynamical systems have been extensively studied in the literature. Since time delay can severely degrade system performance and in many cases drive the system to instability, stability analysis of time-delay dynamical systems remains a very important area of research. Time-delay stability analysis has been mainly classified into two categories, namely, *delay-dependent* and *delay-independent* analysis. Delay-independent stability criteria provide sufficient conditions for stability of time-delay dynamical systems independent of the amount of time delay, whereas delay-dependent stability criteria provide sufficient conditions that are dependent on an upper bound of the time delay. In systems where the time delay is known to be bounded, delay-dependent criteria usually give far less conservative stability predictions as compared to delay-independent results. Hence, for such systems it is of paramount importance to derive the sharpest possible delay-dependent stability margins.

A key method for analyzing stability of time-delay dynamical systems is Lyapunov's second method as applied to functional differential equations. Specifically, stability analysis of a given linear time-delay dynamical system is typically shown using a Lyapunov-Krasovskii functional. These stability criteria may also be interpreted in the frequency domain in terms of a feedback interconnection of a matrix transfer function and a *phase* uncertainty block. Since phase uncertainties have unit gain, delay-independent stability criteria may be derived using the classical small gain theorem or, more generally, the scaled small gain theorem. However, in order to derive delay-dependent stability criteria using the (scaled) small gain approach, one has to perform certain model transformations and then apply the scaled small gain theorem. The necessity for such model transformations lies in the fact that delay-dependent stability criteria may be derived only if we can characterize the phase of the uncertainty in addition to the gain uncertainty.

In this research [43, 47], we present a robust stability analysis method to account for phase uncertainties. Specifically, we develop a general framework for stability analysis of linear systems with structured phase uncertainties. In particular, we introduce the notion of the *structured phase margin* for characterizing stability margins for a dynamical system with block-structured phase uncertainty. In the special case where the uncertainty has no internal structure, the structured phase margin is shown to specialize to the multivariable phase margin given in the literature. Furthermore, since the structured phase margin may be, in general, difficult to compute, we derive an easily computable lower bound in terms of a generalized eigenvalue problem. This bound is constructed by choosing stability multipliers that are tailored to the structure of the phase uncertainty. In addition, using the structured phase margin, we derive new and improved delay-dependent stability criteria for stability analysis of time-delay systems. Even though frequency-domain and integral quadratic constraints (IQCs) have been developed to address the time delay problem, with the notable exception of the literature, all of these results rely on the scaled small gain theorem as applied to a *transformed* system. In contrast, we present new robust stability results for time-delay systems based on pure phase information.

2.18. Frequency Domain Sufficient Conditions for Stability Analysis of Neutral Time-Delay Systems

In the control systems literature, mathematical models of physical/engineering systems and ordinary differential equations are practically synonymous. However, for many physical systems, ordinary differential equations may be inadequate for capturing the dynamic system behavior. Generalizations of ordinary differential equations, such as hybrid system models and functional differential equations, are often necessary in order to capture the complex behavior of some systems. Specifically, in many complex systems such as communication networks involving power transfers between interconnecting system components that are not instantaneous, realistic dynamic models should account for information in transit. Such models lead to time-delay dynamical systems. Time-delay dynamical systems and, more generally, functional differential equations, have been extensively studied in the literature. Functional differential equations have been classified into two categories, namely, *retarded-type* and *neutral-type.* A retarded time-delay differential equation is a differential equation where the time-derivative of the state depends on current state as well as past (delayed) states, while a neutral time-delay differential equation is a differential equation where the time-derivative of the state not only depends on the current and delayed states but also the past (delayed) derivative. Neutral time-delay systems arise in many engineering systems and have been studied extensively in the literature. In this research [85], we study the stability problem for neutral time-delay systems. Specifically, we focus on deriving frequency-domain conditions for linear neutral time-delay systems. The basic idea relies on the fact that the stability characteristics of a linear neutral time-delay system can be studied in terms of a feedback interconnection of a matrix transfer function and a *phase* uncertainty block. Since phase uncertainties have unit gain, many delay-independent stability criteria were derived in the literature using the classical small gain theorem or, more generally, the scaled small gain theorem. Furthermore, many delay-dependent stability criteria were also derived by applying the (scaled) small gain approach on a *transformed* time-delayed system.

In this research, using the structured phase margin [43], we derive several new frequency domain sufficient conditions for stability of linear neutral time-delay systems. We provide both delay-independent as well as delay-dependent sufficient conditions for stability. Since the lower bounds derived in [43] are given in terms of a minimization problem involving linear matrix inequalities all the sufficient conditions presented in this research can be solved as generalized eigenvalue problems.

2.19. Reversibility and Poincaré Recurrence in Linear Dynamical Systems

Reversible dynamical systems tend to exhibit a phenomenon known as *Poincaré recurrence.* Specifically, if the flow of a dynamical system preserves volume and has only bounded orbits, then for each open bounded set there exist orbits that intersect this set infinitely often. It was shown in [31] that Poincaré recurrence for a nonlinear dynamical system is equivalent to the existence of system orbits whose initial conditions belong to their own positive limit sets. Boundedness of the solutions of a dynamical system is crucial in establishing whether or not the dynamical system exhibits Poincaré recurrence. However, for nonlinear dynamical systems, unlike linear systems, boundedness of solutions is not a necessary condition for Poincaré recurrence. Another important condition for the existence of Poincaré recurrence is volume-preservation. In particular, if the flow of a dynamical system is volume-preserving, then, assuming that the system orbits are bounded, the image of any open bounded set under the flow of a dynamical system will eventually intersect the original set at some instant of time, which provides the basis for Poincaré recurrence. However, volume-preservation is not sufficient for ensuring Poincaré recurrence since an unstable system can have a volume-preserving flow with system trajectories never returning to any neighborhood of their initial condition.

In the case of linear dynamical systems, we establish necessary and sufficient conditions for Poincaré recurrence [96]. Specifically, we show that a linear dynamical system exhibits Poincaré recurrence if and only if the system matrix has purely imaginary, semisimple eigenvalues. Furthermore, for linear dynamical systems, we show that a vanishing trace of the system dynamics is a necessary and sufficient condition for volume-preservation. In addition, we show that asymptotically stable and semistable linear systems have volume-decreasing flows, while unstable systems can either have volume-increasing, volume-decreasing, or volume-preserving flows. However, none of these systems exhibit Poincaré recurrence, and hence, these systems are irreversible [31]. Finally, we show that classical lossless linear Lagrangian and Hamiltonian dynamical systems are volume-preserving and exhibit Poincaré recurrence.

2.20. Stability Analysis of Nonlinear Dynamical Systems using Conley index Theory

One of the most basic issues in system theory is stability of dynamical systems. The most complete contribution to stability analysis of nonlinear dynamical systems was introduced in the late nineteenth century by A. M. Lyapunov in his seminal work entitled *The*

General Problem of the Stability of Motion. Lyapunov's results which include the direct and indirect methods, along with the Krasovskii-LaSalle invariance principle, provide a powerful framework for analyzing the stability of equilibrium and periodic solutions of nonlinear dynamical systems. Lyapunov's direct method for examining the stability of an equilibrium state of a dynamical system requires the construction of a positive-definite function of the system states (Lyapunov function) for which its time rate of change due to perturbations in a neighborhood of the system's equilibrium is always negative or zero. Stability of periodic solutions of a dynamical system can also be addressed by constructing a Lyapunov-like function satisfying the Krasovskii-LaSalle invariance principle.

Alternatively, in the case where the trajectory of a dynamical system can be relatively easily integrated, Poincaré's theorem provides a powerful tool in analyzing the stability properties of periodic orbits and limit cycles. Specifically, Poincaré's theorem provides necessary and sufficient conditions for stability of periodic orbits based on the stability properties of a fixed point of a discrete-time dynamical system constructed from a Poincaré return map. However, in many applications, especially for high-dimensional nonlinear systems, system trajectories cannot be relatively easily integrated and the construction of a Lyapunov function for establishing stability properties of a dynamical system can be a daunting task.

In this research [98], we use Conley index theory to develop necessary and sufficient conditions for stability of equilibrium and periodic solutions of nonlinear continuous-time, discrete-time, and impulsive dynamical systems. The Conley index is a topological generalization of Morse theory which has been developed to analyze dynamical systems using topological methods. In particular, the Conley index of an invariant set $\mathcal{S}$ with respect to a dynamical system is defined as the relative homology of an index pair for $\mathcal{S}$. The Conley index can then be used to examine the structure of the system invariant set as well as the system dynamics within the invariant set, including system stability properties. Specifically, Conley index theory is based on isolating neighborhoods of the system state space which enclose components of chain-recurrent sets that can be used to detect connecting orbits between the components of these sets. The method generates a simplicial complex which can be used to provide an understanding of the behavior of sets of trajectories rather than individual orbits of dynamical systems. Efficient numerical algorithms using homology theory have been developed in the literature to compute the Conley index and can be used to deduce the stability properties of nonlinear dynamical systems.

2.21. Controller Analysis and Design for Systems with Input Hystereses Nonlinearities

In recent years the desire to orbit large, lightweight space structures with high-performance requirements has prompted researchers to consider actuators which possess a fraction of the size and weight of more conventional actuation devices. As a consequence, considerable research interest has focused in the field of smart or adaptive materials as a viable alternative to conventional proof mass actuators for vibration control. Due to the fact that adaptation in smart materials is a result of physical nonlinear changes occurring within the material, these actuation devices exhibit significant hysteresis in the actuator response. Specifically, smart distributed actuators such as shape memory alloys, magnetostrictives, electrorheological fluids, and piezoceramics all exhibit hysteretic effects. Since hystereses nonlinearities can severely degrade closed-loop system performance, and in some cases drive the system to a limit cycle instability, they must be accounted for in the control-system design process.

Even though numerous models for capturing hystereses effects have been developed, with the Preisach model being the most widely used, controller analysis and synthesis for feedback systems with hystereses nonlinearities has received little attention in the literature. The main complexity arising in hystereses nonlinearities is the fact that every reachable point in the input-output hysteresis map does not correspond to a uniquely defined point. In fact, at any reachable point in the input-output hysteresis map there exists an infinite number of trajectories that may represent the future behavior of the hysteresis dynamics. These trajectories depend on a particular past history of the extremum values of the input. However, hystereses nonlinearities with counterclockwise loops have been shown to be dissipative with respect to a supply rate involving force inputs and velocity outputs. Dissipative hystereses models include the well known backlash nonlinearities, stiction nonlinearities, relay hystereses, and most of the hystereses nonlinearities arising in smart material actuators.

The contribution of this research [5] is a methodology for analyzing and designing output feedback controllers for systems with input hystereses nonlinearities. Specifically, by transforming the hystereses nonlinearities into dissipative input-output dynamic operators, dissipativity theory is used to analyze and design linear controllers for systems with input hystereses nonlinearities. In particular, by representing the input hysteresis nonlinearity as a dissipative input-output dynamical operator with respect to a given supply rate, partial closed-loop asymptotic stability, that is, asymptotic stability with respect to part of the closed-loop state associated with the plant and the controller, is guaranteed in the face of an input hysteresis nonlinearity. Furthermore, it is shown that the reminder of the state associated with the hysteresis dynamics is semistable, that is, the limit points of the hysteretic states converge to Lyapunov stable equilibrium points determined by the system initial conditions.

3. Research Personnel Supported

Faculty

Wassim M. Haddad, Principal Investigator

Graduate Students

Sergei G. Nersesov, Ph. D.

Qing Hui, Ph. D.

Several other students (T. Hayakawa, J. J. Im, and J. Ricordeau) were involved in research projects that were closely related to this program. Although none of these students were financially supported by this program, their research did directly contribute to the overall research effort. Furthermore, two Ph. D. dissertations were completed under partial support of this program; namely

T. Hayakawa, *Direct Adaptive Control for Nonlinear Uncertain Dynamical Systems*, Ph. D. Dissertation, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, November 2003.

S. G. Nersesov, *Nonlinear Impulsive and Hybrid Dynamical Systems*, Ph. D. Dissertation, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, August 2005.

Dr. Hayakawa holds the rank of Associate Professor of Mechanical and Environmental Informatics at Tokyo Institute of Technology, while Dr. Nersesov is an Assistant Professor of Mechanical Engineering at Villanova University.

4. Interactions and Transitions

4.1. Participation and Presentations

The following conferences were attended over the past three years.

Fourth International Conference on Dynamical Systems and Applications, Atlanta, GA, May 2003.

American Control Conference, Denver, CO, June 2003.

IEEE Conference on Decision and Control, Maui, HI, December 2003.

American Control Conference, Boston, MA, July 2004.

World Congress of Nonlinear Analysts, Orlando, FL, July 2004.

IEEE Conference on Decision and Control, Paradise Island, Bahamas, December 2004.

American Control Conference, Portland, OR, June 2005.

IEEE Conference on Decision and Control, Seville, Spain, December 2005.

Furthermore, conference articles [56–99] were presented.

4.2. Transitions

Our work on adaptive and neuro adaptive control of drug delivery partially supported under this program has transitioned to clinical studies at the Northeast Georgia Medical Center in Gainesville, Georgia, under the direction of Dr. James M. Bailey (770-534-1312), director of cardiac anesthesia and consultant in critical care medicine. To date, we have performed nineteen clinical trials.

In critical care medicine it is current clinical practice to administer potent drugs that profoundly influence levels of consciousness, respiratory, and cardiovascular function by manual control based on the clinician's experience and intuition. Open-loop control by clinical personnel can be tedious, imprecise, time-consuming, and sometimes of poor quality, depending on the skills and judgment of the clinician. Military physicians may face the most demanding of critical care situations when dealing with the causalities of hostile action and in these situations, precise control of the dosing of drugs with potent cardiovascular and central nervous system effects is critical. It has been an aphorism among anesthesiologists since World War II that "thiopental (a common drug for the induction of anesthesia) killed more Americans at Pearl Harbor than the enemy," referring to the consequences of cardiovascular collapse induced by thiopental in trauma patients. Furthermore, military medicine faces unique challenges compared to the civilian sector. The necessity of triage has, sadly, been a not rare event in times of war due to unexpected numbers of causalities overwhelming available resources and furthermore, health care providers may be among the causalities. Because of the possibility of demands on health care providers that may exceed local resources, we believe that it is crucial to investigate the use of advanced control technology to extend the capabilities of the health care system to handle large numbers of causalities. Closed-loop control based on appropriate dynamical system models can improve the quality of drug administration in surgery and the intensive care unit, lessening the dependence of patient outcome on the skills of the clinician.

5. Research Publications

5.1. Journal Articles and Books

[1] S. H. Fu and W. M. Haddad, "Nonlinear adaptive tracking of surface vessels with exogenous disturbances," *Asian J. Control*, vol. 5, pp. 88–103, 2003.

[2] V. Chellaboina and W. M. Haddad, "Authors' reply to comments on Is the Frobenius matrix norm induced?," *IEEE Trans. Autom. Contr.*, vol. 48, pp. 519–520, 2003.

[3] W. M. Haddad, T. Hayakawa, and J. M. Bailey, "Adaptive control for nonnegative and compartmental dynamical systems with applications to general anesthesia," *Int. J. Adapt. Control Signal Process.*, vol. 17, pp. 209–235, 2003.

[4] W. M. Haddad, S. G. Nersesov, and V. Chellaboina, "Energy-based control for hybrid port-controlled Hamiltonian Systems," *Automatica*, vol. 39, pp. 1425–1435, 2003.

[5] W. M. Haddad, V. Chellaboina, and J. Oh, "Linear controller analysis and design for systems with input hystereses nonlinearities," *J. Franklin Inst.*, vol. 340, pp. 371–390, 2003.

[6] V. Chellaboina and W. M. Haddad, "Exponentially dissipative dynamical systems: A nonlinear extension of strict positive realness," *J. Math. Prob. Engin.*, vol. 2003, pp. 25–45, 2003.

[7] A. Roup, D. S. Bernstein, S. G. Nersesov, W. M. Haddad, and V. Chellaboina, "Limit cycle analysis of the verge and foliot clock escapement using impulsive differential equations and Poincaré maps," *Int. J. Contr.*, vol. 76, pp. 1685–1698, 2003.

[8] W. M. Haddad, V. Chellaboina, and E. August, "Stability and dissipativity theory for discrete-time nonnegative and compartmental dynamical systems," *Int. J. Contr.*, vol. 76, pp. 1845–1861, 2003.

[9] V. Chellaboina, W. M. Haddad, J. M. Bailey, and J. Ramakrishnan, "On nonoscillation and monotonicity of solutions of nonnegative and compartmental dynamical systems," *IEEE Trans. Biomed. Eng.*, vol. 51, pp. 408–414, 2004.

[10] S. G. Nersesov, W. M. Haddad, and V. Chellaboina, "Optimal fixed-structure control for linear nonnegative dynamical systems," *Int. J. Robust and Nonlinear Control*, vol. 14, pp. 487–511, 2004.

[11] T. Hayakawa, W. M. Haddad, and A. Leonessa, "A Lyapunov-based adaptive control framework for discrete-time nonlinear systems with exogenous disturbances," *Int. J. Contr.*, vol. 77, pp. 250–263, 2004.

[12] W. M. Haddad and V. Chellaboina, "Stability theory for nonnegative and compartmental dynamical systems with time delay," *Sys. Contr. Lett.*, vol. 51, pp. 355–361, 2004.

[13] W. M. Haddad, Q. Hui, V. Chellaboina, and S. G. Nersesov "Vector dissipativity theory for discrete-time large-scale nonlinear dynamical systems," *Adv. Diff. Eqs.*, vol. 2004, pp. 37–66, 2004.

[14] W. M. Haddad and V. Chellaboina, "Stability and dissipativity theory for nonnegative and compartmental dynamical systems with time delay," in *Advances in Time-Delay Systems*, vol. 38, S.-I. Niculescu and K. Gu Eds., Springer, pp. 421–435, 2004.

[15] W. M. Haddad, V. Chellaboina, and T. Rajpurohit, "Dissipativity theory for nonnegative and compartmental dynamical systems with time delay," *IEEE Trans. Autom. Contr.*, vol. 49, pp. 747–751, 2004.

[16] W. M. Haddad, V. Chellaboina, and S. G. Nersesov, "Thermodynamics and large-scale nonlinear dynamical systems: A vector dissipative systems approach," *Dyn. Cont. Disc. Impl. Syst.*, vol. 11, pp. 609–649, 2004.

[17] W. M. Haddad, S. G. Nersesov, and V. Chellaboina, "A Lyapunov function proof of Poincaré's theorem," *Int. J. Syst. Sci.*, vol. 35, pp. 287–292, 2004.

[18] W. M. Haddad and T. Hayakawa, "Adaptive control for nonlinear nonnegative dynamical systems," *Automatica*, vol. 40, pp. 1637–1642, 2004.

[19] V. Chellaboina, W. M. Haddad, J. M. Bailey, and J. Ramakrishnan, "On monotonicity of solutions of discrete-time nonnegative and compartmental dynamical systems," *Adv. Diff. Eqs.*, vol. 2004, pp. 261–271, 2004.

[20] W. M. Haddad, V. Chellaboina, Q. Hui, and S. G. Nersesov, "Vector dissipativity theory for large-scale impulsive dynamical systems," *J. Math. Prob. Engin.*, vol. 2004, pp. 225–262, 2004.

[21] W. M. Haddad, V. Chellaboina, and S. G. Nersesov, "Vector dissipativity theory and stability of feedback interconnections for large-scale nonlinear dynamical systems," *Int. J. Contr.*, vol. 77, pp. 907–919, 2004.

[22] W. M. Haddad and V. Chellaboina, "Stability and dissipativity theory for nonnegative dynamical systems: A unified analysis framework for biological and physiological systems," *Nonlinear Anal.: Real World Applications*, vol. 6, pp. 35–65, 2005.

[23] V. Chellaboina, W. M. Haddad, and A. Kamath, "A dissipative dynamical systems approach to stability analysis of time delay systems," *Int. J. Robust and Nonlinear Control*, vol. 15. pp. 25–33, 2005.

[24] T. Hayakawa, W. M. Haddad, J. M. Bailey, and N. Hovakimyan, "Passivity-based neural network adaptive output feedback control for nonlinear nonnegative dynamical systems," *IEEE Trans. Neural Networks*, vol. 16, pp. 387–398, 2005.

[25] T. Hayakawa, W. M. Haddad, N. Hovakimyan, and V. Chellaboina, "Neural network adaptive control for nonlinear nonnegative dynamical systems," *IEEE Trans. Neural Networks*, vol. 16, pp. 399–413, 2005.

[26] J. M. Bailey and W. M. Haddad, "Drug dosing control in clinical pharmacology: Paradigms, benefits, and challenges," *IEEE Contr. Syst. Mag.*, vol. 25, pp. 35–51, 2005.

[27] W. M. Haddad, T. Hayakawa, S. G. Nersesov, and V. Chellaboina, "Hybrid adaptive control for nonlinear impulsive dynamical systems," *Int. J. Adapt. Control Signal Process.*, vol. 19, pp. 445–469, 2005.

[28] W. M. Haddad, N. A. Kablar, V. Chellaboina, and S. G. Nersesov, "Optimal disturbance rejection control for nonlinear impulsive dynamical systems," *Nonlinear Analysis*, vol. 62, pp. 1466–1489, 2005.

[29] W. M. Haddad, Q. Hui, S. G. Nersesov, and V. Chellaboina, "Thermodynamic modeling, energy equipartition, and entropy for discrete-time dynamical systems," *Adv. Diff. Eqs.*, vol. 2005, pp. 275–318, 2005.

[30] Q. Hui, W. M. Haddad, V. Chellaboina, and T. Hayakawa, "Adaptive control of mammillary drug delivery systems with actuator amplitude constraints and system time delays," *Eur. J. Contr.*, vol. 11, pp. 586–600, 2005.

[31] W. M. Haddad, V. Chellaboina, and S. G. Nersesov, *Thermodynamics: A Dynamical Systems Approach*, Princeton, NJ: Princeton Univ. Press, 2005.

[32] W. M. Haddad, T. Hayakawa, and J. M. Bailey, "Adaptive control for nonlinear compartmental dynamical systems with applications to clinical pharmacology," *Syst. Contr. Lett.*, vol. 55, pp. 62–70, 2006.

[33] S. G. Nersesov and W. M. Haddad, "On the stability and control of nonlinear dynamical systems via vector Lyapunov functions," *IEEE Trans. Autom. Contr.*, vol. 51, pp. 203–215, 2006.

[34] W. M. Haddad and Q. Hui, "Energy dissipating hybrid control for impulsive dynamical systems," *Nonlinear Analysis*, to appear.

[35] W. M. Haddad, T. Hayakawa, and M. C. Stasko, "Direct adaptive control for nonlinear matrix second-order systems with time-varying and sign-indefinite damping and stiffness operators," *Asian J. Control*, to appear.

[36] W. M. Haddad Q. Hui, V. Chellaboina, and S. G. Nersesov, "Hybrid decentralized maximum entropy control for large-scale dynamical systems," *Nonlinear Analysis*, to appear.

[37] S. G. Nersesov and W. M. Haddad, "On the stability and control of nonlinear impulsive dynamical systems via vector Lyapunov functions," *Nonlinear Analysis*, to appear.

[38] W. M. Haddad, N. A. Kablar, and V. Chellaboina, "Nonlinear robust control for nonlinear uncertain impulsive dynamical systems," *Nonlinear Analysis*, submitted.

[39] A. Leonessa, W. M. Haddad, and T. Hayakawa, "Adaptive control for nonlinear uncertain systems with actuator amplitude and rate saturation constraints," *Automatica*, submitted.

[40] D. S. Bernstein, S. P. Bhat, W. M. Haddad, and V. Chellaboina, "Nonnegativity, reducibility, and semistability of mass action kinetics," *Int. J. Contr.*, submitted.

[41] A. Leonessa, V. Chellaboina, W. M. Haddad, and T. Hayakawa, "Direct discrete-time adaptive control with guaranteed parameter error convergence," *IEEE Trans. Autom. Contr.*, submitted.

[42] W. M. Haddad, V. Chellaboina, Q. Hui, and T. Hayakawa, "Neural network adaptive control for discrete-time nonlinear nonnegative dynamical systems," *Neural Networks*, submitted.

[43] V. Chellaboina, W. M. Haddad, and A. Kamath, "The structured phase margin for stability analysis of linear systems with phase and time delay uncertainties," *IEEE Trans. Autom. Contr.*, submitted.

[44] V. Chellaboina, W. M. Haddad, J. Ramakrishnan, and J. M. Bailey, "On monotonicity of solutions of nonnegative and compartmental dynamical systems with time delay," *Automatica*, submitted.

[45] W. M. Haddad, V. Chellaboina, and S. G. Nersesov, "Time-reversal symmetry, Poincaré recurrence, irreversibility, and the entropic arrow of time: From mechanics to system thermodynamics," *Physica D*, submitted.

[46] V. Chellaboina, W. M. Haddad, J. Ramakrishnan, and T. Hayakawa, "Direct adaptive control of nonnegative and compartmental systems with time delay," *Int. J. Adapt. Control Signal Process.*, submitted.

[47] V. Chellaboina, W. M. Haddad, and A. Kamath, "New sufficient conditions for stability analysis of time delay systems using dissipativity theory," *Int. J. Contr.*, submitted.

[48] W. M. Haddad, J. Bailey, T. Hayakawa, and N. Hovakimyan, "Neural network adaptive output feedback control for intensive care unit sedation and intraoperative anesthesia," *IEEE Trans. Neural Networks*, submitted.

[49] V. Chellaboina and W. M. Haddad, "On the equivalence between dissipativity theory and Lyapunov bounding theory for robust stability analysis," *Automatica*, submitted.

[50] V. Chellaboina, W. M. Haddad, Q. Hui, and J. Ramakrishnan, "On state equipartitioning and semistability in network dynamical systems with arbitrary time-delays," *IEEE Trans. Autom. Contr.*, submitted.

[51] V. Chellaboina, W. M. Haddad, and A. Kamath, "Stability of feedback interconnections via dissipativity theory with dynamic supply rates," *J. Math. Prob. Engin.*, submitted.

[52] T. Hayakawa, W. M. Haddad, and N. Hovakimya, "Neural network adaptive control for nonlinear uncertain dynamical systems with asymptotic stability guarantees," *IEEE Trans. Neural Networks*, submitted.

[53] Q. Hui and W. M. Haddad, "Subspace identification of stable nonnegative and compartmental dynamical systems via constrained optimization," *Int. J. Contr.*, submitted.

[54] W. M. Haddad, V. Chellaboina, Q. Hui, and S. G. Nersesov, "Energy and entropy based stabilization for lossless dynamical systems via hybrid controllers," *IEEE Trans. Autom. Contr.*, submitted.

[55] J. M. Bailey, W. M. Haddad, J. J. Im, and T. Hayakawa, "Adaptive and neural network adaptive control of depth of anesthesia during surgery," *Anesthesiology*, submitted.

5.2. Conference Articles

[56] T. Hayakawa, W. M. Haddad, N. Hovakimyan, and V. Chellaboina, "Neural network adaptive control for nonlinear nonnegative dynamical systems," in *Proc. Amer. Contr. Conf.*, pp. 561–566, (Denver, CO), June 2003.

[57] W. M. Haddad, V. Chellaboina, and T. Rajpurohit, "Dissipativity theory for nonnegative and compartmental dynamical systems with time delay," in *Proc. Amer. Contr. Conf.*, pp. 857–862, (Denver, CO), June 2003.

[58] V. Chellaboina, W. M. Haddad, and A. Kamath, "A dissipative dynamical systems approach to stability analysis of time delay systems," in *Proc. Amer. Contr. Conf.*, pp. 863–868, (Denver, CO), June 2003.

[59] W. M. Haddad, T. Hayakawa, and J. M. Bailey, "Nonlinear adaptive control for intensive care unit sedation and operating room hypnosis," in *Proc. Amer. Contr. Conf.*, pp. 1808–1813, (Denver, CO), June 2003.

[60] V. Chellaboina, W. M. Haddad, J. M. Bailey, and J. Ramakrishnan, "On monotonicity of solutions of discrete-time nonnegative and compartmental dynamical systems," in *Proc. Amer. Contr. Conf.*, pp. 2329–2334, (Denver, CO), June 2003.

[61] W. M. Haddad, M. C. Stasko, and T. Hayakawa, "Direct adaptive control for nonlinear matrix second-order systems with time-varying and sign-indefinite damping and stiffness operators," in *Proc. Amer. Contr. Conf.*, pp. 2919–2924, (Denver, CO), June 2003.

[62] A. Leonessa, V. Chellaboina, W. M. Haddad, and T. Hayakawa, "Direct discrete-time adaptive control with guaranteed parameter error convergence," in *Proc. Amer. Contr. Conf.*, pp. 2925–2930, (Denver, CO), June 2003.

[63] S. G. Nersesov, W. M. Haddad, and V. Chellaboina, "Optimal fixed-structure control for linear nonnegative dynamical systems," in *Proc. Amer. Contr. Conf.*, pp. 3496–3501, (Denver, CO), June 2003.

[64] W. M. Haddad, V. Chellaboina, and S. G. Nersesov, "A unification between partial stability of state-dependent impulsive systems and stability theory of time-dependent impulsive systems," in *Proc. Amer. Contr. Conf.*, pp. 4004–4009, (Denver, CO), June 2003.

[65] W. M. Haddad, T. Hayakawa, S. G. Nersesov, and V. Chellaboina, "Hybrid adaptive control for nonlinear impulsive dynamical systems," in *Proc. Amer. Contr. Conf.*, pp. 5110–5115, (Denver, CO), June 2003.

[66] V. Chellaboina, W. M. Haddad, J. Ramakrishnan, and J. M. Bailey, "On monotonicity of solutions of nonnegative and compartmental dynamical systems with time delay," in *Proc. IEEE Conf. Dec. Contr.*, pp. 4008–4013, (Maui, HI), December 2003.

[67] V. Chellaboina, W. M. Haddad, S. Kalavagunta, and A. Kamath, "Structured phase margin for stability analysis of linear systems with time delay," in *Proc. IEEE Conf. Dec. Contr.*, pp. 5035–5040, (Maui, HI), December 2003.

[68] W. M. Haddad, V. Chellaboina, and S. G. Nersesov, "Large-scale nonlinear dynamical systems: A vector dissipative systems approach," in *Proc. IEEE Conf. Dec. Contr.*, pp. 5603–5608, (Maui, HI), December 2003.

[69] W. M. Haddad, V. Chellaboina, Q. Hui, and T. Hayakawa, "Neural network adaptive control for discrete-time nonlinear nonnegative dynamical systems," in *Proc. IEEE Conf. Dec. Contr.*, pp. 5691–5696, (Maui, HI), December 2003.

[70] T. Hayakawa, W. M. Haddad, J. M. Bailey, and N. Hovakimyan, "Passivity-based neural network adaptive output feedback controk for nonlinear nonnegative dynamical systems," in *Proc. IEEE Conf. Dec. Contr.*, pp. 5697–5702, (Maui, HI), December 2003.

[71] W. M. Haddad, V. Chellaboina, and S. G. Nersesov, "A system-theoretic foundation for thermodynamics: Energy flow, energy balance, energy equipartition, entropy, and ectropy," in *Proc. Amer. Contr. Conf.*, pp. 396–417, (Boston, MA), July 2004.

[72] V. Chellaboina, W. M. Haddad, J. Ramakrishnan, and T. Hayakawa, "Direct adaptive control of nonnegative and compartmental systems with time delay," in *Proc. Amer. Contr. Conf.*, pp. 1235–1240, (Boston, MA), July 2004.

[73] W. M. Haddad and V. Chellaboina, "Stability theory for nonnegative and compartmental dynamical systems with time delay," in *Proc. Amer. Contr. Conf.*, pp. 1422–1427, (Boston, MA), July 2004.

[74] W. M. Haddad, T. Hayakawa, and V. Chellaboina, "Hybrid direct adaptive stabilization for nonlinear impulsive dynamical systems," in *Proc. Amer. Contr. Conf.*, pp. 1885–1890, (Boston, MA), July 2004.

[75] J. M. Bailey, W. M. Haddad, and T. Hayakawa, "Closed-loop control in clinical pharmacology: Paradigms, benefits, and challenges," in *Proc. Amer. Contr. Conf.*, pp. 2268–2277, (Boston, MA), July 2004.

[76] W. M. Haddad, Q. Hui, V. Chellaboina, and S. G. Nersesov, "Vector dissipativity theory for discrete-time large-scale nonlinear dynamical systems," in *Proc. Amer. Contr. Conf.*, pp. 3699–3704, (Boston, MA), July 2004.

[77] V. Chellaboina, W. M. Haddad, and A. Kamath, "New sufficient conditions for stability analysis of time delay systems using dissipativity theory," in *Proc. Amer. Contr. Conf.*, pp. 4171–4176, (Boston, MA), July 2004.

[78] T. Hayakawa, W. M. Haddad, N. Hovakimyan, and J. M. Bailey, "Neural network adaptive dynamic output feedback control for nonlinear nonnegative systems using tapped delay memory units," in *Proc. Amer. Contr. Conf.*, pp. 4505–4510, (Boston, MA), July 2004.

[79] W. M. Haddad, V. Chellaboina, and S. G. Nersesov, "Vector dissipativity theory for large-scale nonlinear dynamical systems," in *Proc. IEEE Conf. Dec. Contr.*, pp. 3424–3429, (Paradise Island, Bahamas), December 2004.

[80] S. G. Nersesov and W. M. Haddad, "On the stability and control of nonlinear dynamical systems via vector Lyapunov functions," in *Proc. IEEE Conf. Dec. Contr.*, pp. 4107–4112, (Paradise Island, Bahamas), December 2004.

[81] Q. Hui, W. M. Haddad, V. Chellaboina, and T. Hayakawa, "Adaptive control of mammillary drug delivery systems with actuator amplitude constraints and system time delays," in *Proc. Amer. Contr. Conf.*, pp. 967–972, (Portland, OR), June 2005.

[82] T. Hayakawa, W. M. Haddad, and N. Hovakimyan, "Neural network adaptive control for nonlinear uncertain dynamical systems with asymptotic stability guarantees," in *Proc. Amer. Contr. Conf.*, pp. 1301–1306, (Portland, OR), June 2005.

[83] W. M. Haddad, Q. Hui, S. G. Nersesov, and V. Chellaboina, "Thermodynamic modeling, energy equipartition, and entropy for discrete-time dynamical systems," in *Proc. Amer. Contr. Conf.*, pp. 4832–4837, (Portland, OR), June 2005.

[84] T. Hayakawa, W. M. Haddad, and N. Hovakimyan, "A new characterization for stable neural network control for discrete-time uncertain systems," in *Proc. IFAC World Cong.*, (Prague, Czech Republic), July 2005.

[85] V. Chellaboina, A. Kamath, and W. M. Haddad, "Frequency domain sufficient conditions for stability analysis of linear neutral time-delay systems," in *Proc. IEEE Conf. Dec. Contr.*, pp. 4330–4335, (Seville, Spain), December 2005.

[86] V. Chellaboina, W. M. Haddad, and A. Kamath, "Dynamic dissipativity theory for stability of nonlinear feedback dynamical systems," in *Proc. IEEE Conf. Dec. Contr.*, pp. 4748–4753, (Seville, Spain), December 2005.

[87] W. M. Haddad, V. Chellaboina, Q. Hui, and S. G. Nersesov, "Thermodynamic stabilization via energy dissipating hybrid controllers," in *Proc. IEEE Conf. Dec. Contr.*, pp. 4879–4884, (Seville, Spain), December 2005.

[88] T. Hayakawa and W. M. Haddad, "Stable neural hybrid adaptive control for nonlinear uncertain impulsive dynamical systems," in *Proc. IEEE Conf. Dec. Contr.*, pp. 5510–5515, (Seville, Spain), December 2005.

[89] W. M. Haddad, V. Chellaboina, and S. G. Nersesov, "Time-reversal symmetry, Poincaré recurrence, irreversibility, and the entropic arrow of time: From mechanics to system thermodynamics," in *Proc. IEEE Conf. Dec. Contr.*, pp. 5995–6002, (Seville, Spain), December 2005.

[90] W. M. Haddad, Q. Hui, V. Chellaboina, and S. G. Nersesov, "Hybrid decentralized maximum entropy control for large-scale dynamical systems," in *Proc. Amer. Contr. Conf.*, (Minneapolis, MN), June 2006.

[91] Q. Hui and W. M. Haddad, "Subspace identification of stable nonnegative and compartmental dynamical systems via constrained optimization," in *Proc. Amer. Contr. Conf.*, (Minneapolis, MN), June 2006.

[92] V. Chellaboina, W. M. Haddad, and A. Kamath, "New time-domain conditions for stability analysis of linear time-delay systems," in *Proc. Amer. Contr. Conf.*, (Minneapolis, MN), June 2006.

[93] V. Chellaboina, W. M. Haddad, J. Ramakrishnan, and T. Hayakawa, "Adaptive control for nonnegative dynamical systems with arbitrary time delay," in *Proc. Amer. Contr. Conf.*, (Minneapolis, MN), June 2006.

[94] W. M. Haddad and Q. Hui, "Energy dissipating hybrid control for impulsive dynamical systems," in *Proc. Amer. Contr. Conf.*, (Minneapolis, MN), June 2006.

[95] J. M. Bailey, W. M. Haddad, J. J. Im, and T. Hayakawa, "Adaptive and neural network adaptive control of depth of anesthesia during surgery," in *Proc. Amer. Contr. Conf.*, (Minneapolis, MN), June 2006.

[96] S. G. Nersesov and W. M. Haddad, "Reversibility and Poincaré recurrence in linear dynamical systems" in *Proc. Amer. Contr. Conf.*, (Minneapolis, MN), June 2006.

[97] V. Chellaboina, W. M. Haddad, Q. Hui, and J. Ramakrishnan, "On state equipartitioning and semistability in network dynamical systems with arbitrary time-delays," in *Proc. IEEE Conf. Dec. Contr.*, (San Diego, CA), December 2006.

[98] Q. Hui and W. M. Haddad, "Stability analysis of nonlinear dynamical systems using Conley index theory," in *Proc. IEEE Conf. Dec. Contr.*, (San Diego, CA), December 2006.

[99] S. G. Nersesov and W. M. Haddad, "On the stability and control of nonlinear impulsive dynamical systems via vector Lyapunov functions," in *Proc. IEEE Conf. Dec. Contr.*, (San Diego, CA), December 2006.