PASSIVITY AND DISSIPATIVITY IN RESILIENT CPS DESIGN

Results of Antsaklis' group at the University of Notre Dame
2008-2018

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Etika Agarwal, Arash Rahnama, Yang Yan, Hasan Zakeri
and Panos J. Antsaklis
Department of Electrical Engineering
Unversity of Notre Dame
Notre Dame, IN 46556

Interdisciplinary Studies in Intelligent Systems

Abstract

Around 2008, the Antsaklis' research group at Notre Dame started using the energy like concept of passivity as the central concept in the design of Cyber-Physical Systems (CPS). CPS are large interconnected heterogeneous systems that may change dynamically. Using passivity and its generalization of dissipativity, the group was able to address compositionality and resilience in CPS that make it possible to preserve important properties under feedback interconnections and uncertainties quite effectively. This report is a summary of the results on Passivity and Dissipativity covering approximately the years 2008-2018. The collected results have been derived by the following PhD students and collaborators.

PhD students	Etika Agarwal (Current student)	Yang Yan (Current student)	Hasan Zakeri (Current student)
	Arash Rahnama (PhD May 2018)	Vahideh Ghanbari (PhD May 2017)	Meng Xia (PhD May 2015)
	Feng Zhu (PhD May 2014)	Michael McCourt (PhD May 2013)	Po Wu (PhD May 2013)
	Han Yu (PhD May 2013)	Eloy Garcia (PhD May 2012)	Tomas Estrada (PhD May 2009)
	Nicholas Kottenstette (PhD May 2007)	Luis Montestruque (PhD May 2005)	
Collaborators	Sivaranjani S.	Sravan Sajja	Vijay Gupta
	Yue Wang	Shige Wang	Getachew Befekadu

Contents

Chapter 1

Passivity and Dissipativity

References: [1]–[9][T1]

1.1 Introduction

Passivity is an appealing concept. It is a dynamic system characterization based on energy dissipation. Passive system is one that stores and dissipates energy without generating its own. This approach is very intuitive for physical systems [1]–[8].

The concept of passivity is quite general and it has been applied to a wide variety of systems with arbitrary nonlinear dynamics, as covered in the following sections. The passive systems theory is mathematically similar to the Lyapunov stability theory, but it is applicable to a smaller class of systems, that is, it is more restrictive. These added restrictions make Lyapunov theory more attractive for stability analysis of a single system, than passivity theory. Note that a passive system is stable. However, there are additional benefits to the passivity based approach. The most useful benefit from a controls perspective is that passivity is a property that is preserved when systems are interconnected in parallel or in feedback configurations. This means that practical interconnections of passive systems that include feedback and parallel interconnections are stable. Passivity allows for simple design of stable complex systems. This assumes that each system component is passive or can be made passive with a local controller. If these components are sequentially connected in parallel or in feedback the entire interconnection is passive and stable.

Passivity has been applied to many systems using the traditional notion of energy. Examples include simple systems such as electrical circuits and mass-spring-dampers. More complex applications include robotics, distributed systems, and chemical processes. It has also been applied to networked control systems with time-varying delays. In this case, the feedback interconnection with delays is made passive using the wave variable transformation (see section 9 for details). In these more general cases, passivity can be applied even when there is not a traditional notion of energy, but rather of a generalized energy. This generalized energy can be defined for each specific system using an energy storage function and a supply rate function. When a storage function exists and the energy stored in a system can be bounded above by the energy supplied to the system, the system is called to be dissipative. Passivity can be obtained as a special case of dissipativity for specific supply rate function.

Dissipativity has shown great promise in the design of Cyber-Physical Systems (CPS). Its relevance to CPS design stems from the fact that this concept can be extended to more general hybrid/switched systems, dissipative systems exhibit a compositional property for parallel and negative feedback (more generally, power-conserving) interconnections [5], [6], and its ability to deal with uncertainty in the plant. More results on applications of passivity and dissipativity in design of CPS can be found in the coming sections and in [9].

1.2 Definitions

For a continuous-time dynamical system $\Sigma : U \longrightarrow Y$, there exists an associated real-valued function $w(u(t), y(t))$(or $w(t)$ if clear from the context) defined on $U \times Y$, called *supply rate.* We assume that $w(t)$ satisfies

$$\int_{t_0}^{t_1} |w(t)| d(t) < \infty, \tag{1.1}$$

for any $t_0, t_1 \in \mathbb{R}_0^+$, $t_1 > t_0$ and any input $u(t) \in U$. Analogously, for a discrete time dynamical system $\Sigma_d : U \longrightarrow Y$ we assume that the supply rate $W(u(k), y(k))$(or $W(k)$) defined on $U \times Y$ satisfies

$$\sum_{k=k_0}^{k_1} |W(k)| < \infty, \tag{1.2}$$

for any $k_0, k_1 \in \mathbb{Z}_0^+$, $k_1 > k_0$ and any input $u(k) \in U$.

The definitions of dissipativity and its variants presented in the following subsections are detailed in [3]–[5].

1.2.1 Input-Output Representation

A dynamical system represented as an input-output operator $\mathcal{H} : u \mapsto y$ is called *dissipative* with respect to a supply rate function $w(u(t), y(t))$, if there exists a constant $\beta \leq 0$, such that for all $t_1 \geq t_0$, and all $u \in U$ and the corresponding output y,

$$\int_{t_0}^{t_1} w(u(t), y(t)) dt \geq \beta \tag{1.3}$$

The constant β is related to the initial conditions of the system $\mathcal{H}$ and plays an important role in the stability analysis of the system [7].

1.2.2 State-Space Representation

A dynamical system can be represented in two general forms: an input-output map, or a state-space description. Passivity can be defined for either of these forms. While passivity is an input-output property, the state-space description is useful in understanding its relationship with traditional stability notions since energy is a function of the state.

Consider a continuous-time nonlinear system with dynamics given by

$$\begin{aligned} \dot{x} &= f(x,u), \\ y &= h(x,u) \end{aligned} \tag{1.4}$$

where f and h are smooth mappings of appropriate dimensions, $u \in \mathbb{U}$ and $y \in \mathbb{Y}$ are inputs and outputs of the system, and $x \in X \subset \mathbb{R}^n$ is the system state. Without loss of generality, we assume that the pair $(x = 0, u = 0)$ is an equilibrium point for the system. This system is said to be ***dissipative*** with respect to supply rate $w(u(t), y(t))$, if there exists a non-negative function $V(x)$, called the storage function, satisfying $V(0) = 0$ such that for all $x_0 \in X$, all $t_1 \geq t_0$, and all $u \in \mathbb{R}^m$,

$$\int_{t_0}^{t_1} w(u(t), y(t))dt \geq V(x(t_1)) - V(x(t_0)), \tag{1.5}$$

where $x(t_0) = x_0$ and $x(t_1)$ is the state at t_1 resulting from initial condition x_0 and input function $u(\cdot)$. In particular, if (1.5) holds with strict inequality, then system (1.4) is called ***strictly dissipative***. If $V(x)$ is differentiable, (1.5) is equivalent to

$$w(u, y) \geq \dot{V}(x) := \frac{\partial V}{\partial x} f(x, u). \tag{1.6}$$

We are particularly interested in the case when $w(t)$ is quadratic in u and y. More formally, a dynamical system is called ***QSR-dissipative*** if its supply rate is given by

$$w(u, y) = y^\intercal Q y + 2y^\intercal S u + u^\intercal R u, \tag{1.7}$$

where $Q = Q^\intercal, S$ and $R = R^\intercal$ are matrices of appropriate dimension. One reason for considering such quadratic supply rate is that by setting Q, S and R to be in particular forms, we can obtain various notions of passivity and $\mathcal{L}_2$ stability. For instance, if a system is dissipative with supply rate given by (1.7) where $R = \gamma^2 I, S = 0$ and $Q = I$, then the system is $\mathcal{L}_2$ stable with finite gain $\gamma > 0$.

Now suppose system (1.4) is QSR-dissipative. It is called:

1. passive if $Q = 0$, $S = \frac{1}{2}I$, $R = 0$;
2. strictly passive (SP) if (1.7) holds with strict inequality for $Q = 0$, $S = \frac{1}{2}I$, $R = 0$;

3. input strictly passive (ISP) if $Q = 0$, $S = \frac{1}{2}I$, $R = -\nu I$ where $\nu > 0$;

4. output strictly passive (OSP) if $Q = -\rho I$, $S = \frac{1}{2}I$, $R = 0$ where $\rho > 0$;

5. very strictly passive (VSP) if $Q = -\rho I$, $S = \frac{1}{2}I$, $R = \nu I$ where $\rho > 0$ and $\nu > 0$;

6. finite-gain $\mathcal{L}_2$ stable if there exists a constant $\gamma \neq 0$ such that $Q = -I$, $S = 0$, $R = \gamma^2 I$, denoted as $FGS(\gamma)$;

7. strictly passive and input strictly passive (SSIP) if it is simultaneously SP and ISP.

Remark: Dissipativity notions obtained as per specialized storage functions (QSR, ISP, OSP etc.) described above, hold for the input-output representation of dissipative systems in 1.3 as well. **An equivalence between the input-output and state-space representations of dissipativity is established in [8, Proposition 3].** The relationship between several other notions of passivity and dissipativity is presented in [7]. Time domain and frequency domain conditions for passivity are discussed in [T1].

1.3 Passivity Indices

It is a well known result in literature that the negative feedback and parallel interconnection of two passive systems remains passive (more on this in section 1.4). However, if one of the systems is not passive, it is still possible that an "excess of passivity" (stronger than passivity) of the other system can still assure that the interconnected system is passive. This "excess" or "shortage" of passivity in a system can be indicated by a measure for level of passivity, known as passivity index. A dynamical system is said to be

1. input feedforward passive (IFP) if it is dissipative with respect to supply rate $w(u, y) = u^\intercal y - \nu u^\intercal u$ for some $\nu \in \mathbb{R}$, denoted as IFP(ν); we call such a ν an IFP level, and the largest IFP level is called the IFP index. This is equivalent to the largest gain that can be put in negative feedforward interconnection with the system such that the interconnection remains passive. Figure 1.1 depicts this configuration.

2. output feedback passive (OFP) if it is dissipative with respect to supply rate $w(u, y) = u^\intercal y - \rho y^\intercal y$ for some $\rho \in \mathbb{R}$, denoted as OFP(ρ); we call such a ρ an OFP level, and the largest OFP level ρ is called the OFP index. This is equivalent to the largest gain that can be put in positive feedback with the system, such that the interconnection remains passive. Figure 1.2 depicts this configuration.

3. input-feedforward-output-feedback passive (IF-OFP) if there exist constants δ and ϵ so that $w(u, y) = u^\intercal y - \delta y^\intercal y - \epsilon u^\intercal u$, denoted as IF-OFP($\epsilon, \delta$); we call such δ and ϵ passivity levels.

Clearly, if either one of two passivity indices is positive, we say that the system has an 'excess of passivity'; similarly, if either one of the two passivity indices is negative, we say that the system has a 'shortage of passivity'. Note that it is not possible to have one index positive and the other negative, simultaneously. Yu et al in [10] briefly discuss a meaningful domain for passivity indices.

1.4 Fundamental Results

Passive and dissipative systems exhibit two main properties which make them especially attractive for control design and analysis; first, the passivity and dissipativity of an interconnected system can potentially be implied from that of its components. This is especially important when we analyze large-scale systems [9]. Second, passivity implies stability under mild assumptions. In this section, we briefly present these fundamental results in dissipativity and passivity theories. We refer the reader to [5], [6].

1.4.1 Dissipativity of Interconnected Systems

Consider a negative feedback interconnection of two systems, say Σ_1 and Σ_2, with inputs u_i and outputs y_i, $i \in \{1, 2\}$, as shown in Figure 1.3, and assume $u_1 = r_1 - y_2$ and $u_2 = y_1 + r_2$. If system Σ_i is dissipative with quadratic supply rate w_i

$$w_i(u_i, y_i) = u_i^\intercal R_i u_i + 2y_i^\intercal S_i u_i + y_i^\intercal Q_i y_i \tag{1.8}$$

for all $i \in \{1, 2\}$, then the interconnected system Σ with input $r = [r_1^\intercal \; r_2^\intercal]^\intercal$ and output $y = [y_1^\intercal \; y_2^\intercal]^\intercal$ is also dissipative with quadratic supply rate $w(r, y) = y^\intercal Q y + 2y^\intercal S r + r^\intercal R r$, where

$$Q = \begin{bmatrix} Q_1 + R_2 & -S_1 + S_2^\intercal \\ -S_1^\intercal + S_2 & R_1 + Q_2 \end{bmatrix}, \quad S = \begin{bmatrix} S_1 & R_2 \\ -R_1 & S_2 \end{bmatrix}, \quad R = \begin{bmatrix} R_1 & 0 \\ 0 & R_2 \end{bmatrix}. \tag{1.9}$$

Since passivity and its variants can be thought of as a special case of QSR-dissipativity, the following results can be derived easily from (1.9). A negative feedback interconnection of two systems Σ_1 and Σ_2, as shown in Figure 1.3, is

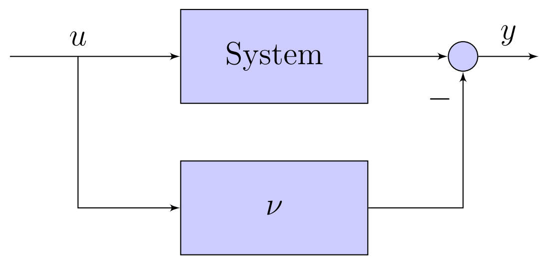

Figure 1.1: Input feedforward passivity index

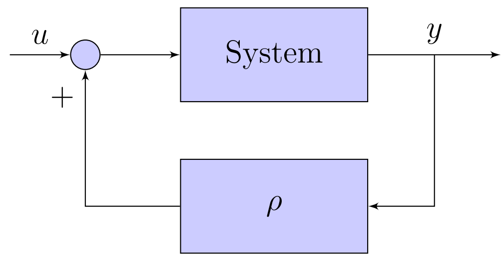

Figure 1.2: Output feedback passivity index

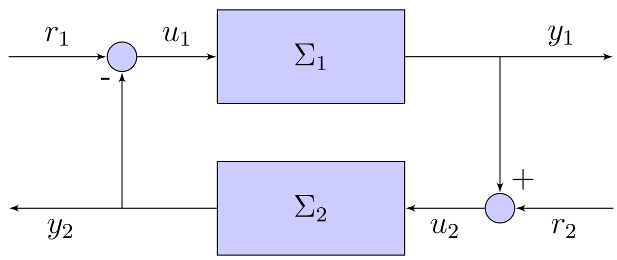

Figure 1.3: Negative feedback interconnection of two systems

- passive if systems Σ_1 and Σ_2 are passive.
- OSP if systems Σ_1 and Σ_2 are OSP.

Next consider the parallel interconnection of two systems, as shown in Figure 1.4. Again, we can obtain the following results:

- If systems Σ_1 and Σ_2 are passive, then the resulting interconnected system Σ is passive.
- If system Σ_1 and Σ_2 are ISP, then the resulting interconnected system Σ is ISP.

Therefore, we can conclude that:

1. Quadratic dissipativity is preserved under feedback interconnections;
2. Passivity is preserved under both parallel and feedback interconnections;
3. ISP is preserved under parallel interconnections;
4. OSP is preserved under negative feedback interconnections.

1.4.2 Stability of Dissipative Systems

The notion of dissipativity is closely related to both internal stability and input-output stability concepts. The following table lists some of the important relationships between dissipative and stable systems.

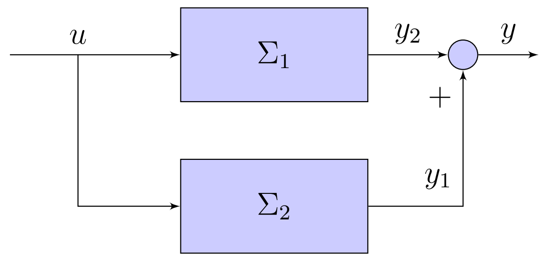

Figure 1.4: Parallel interconnection of two systems

Table 1.1: Stability of dissipative systems.

System Property		Lyapunov Stable	Asymptotically Stable	Finite Gain $\mathcal{L}_2$ Stable
Passive, $V > 0$	$\Longrightarrow$	✓		
ISP, $V > 0$	$\Longrightarrow$	✓		
OSP, $V > 0$ and system is zero-state detectable	$\Longrightarrow$	✓	✓	✓
Strictly Passive, $V > 0$	$\Longrightarrow$	✓	✓	
QSR-Dissipative, $Q < 0$	$\Longrightarrow$			✓

As per Table 1.1, a dynamical system (1.4) is $\mathcal{L}_2$ stable if and only if it is dissipative with (1.7) such that $Q < 0$. The origin of $\dot{x} = f(x, 0)$ is asymptotically stable if the sysetm is strictly passive, or if it is output strictly passive and zero state detectability. Note that a relationship between internal stability and dissipativity requires the storage function $V(\cdot)$ to be positive definite (unlike the $V(\cdot)$ being non-negative in the dissipativity definition described by (1.5)).

As an extension of the stability results in Table 1, we can show that the feedback interconnection given in Figure 1.3 is $\mathcal{L}_2$ stable, if

- Σ_1 is OSP and Σ_2 is passive, or
- Σ_1 and Σ_2 are both ISP, or
- Σ_1 and Σ_2 are both OSP, or
- Σ_1 is VSP and Σ_2 is passive, or
- Σ_1 and Σ_2 are $\mathcal{L}_2$ stable with gain γ_i for $i = 1, 2$ such that $\gamma_1\gamma_2 < 1$.

Also, for the feedback interconnection of two systems Σ_1 and Σ_2,

1. If system Σ_1 is IF-OFP(ϵ_1, δ_1) and Σ_2 is IF-OFP(ϵ_2, δ_2), where $\epsilon_1 + \delta_2 > 0, \epsilon_2 + \delta_1 > 0$, then system Σ is finite gain stable (FGS);

2. Assume that system Σ_1 has OFP(ρ) and system Σ_2 has IFP(ν), where $\rho+\nu > 0$. Then, system Σ has OFP($\rho + \nu$). Further, the system Σ is finite-gain stable (FGS) with gain $\gamma \leq \frac{1}{\rho+\nu}$.

3. Assume that system Σ_1 has IFP($\nu > 0$) and system Σ_2 has OFP(ρ). If $\nu + \rho > 0$, then system Σ has IFP($\min(\nu, \rho + \nu)$.)

Chapter 2

Passivity and Dissipativity in Switched, Hybrid and Discrete Event Systems

References: [11]–[15][T2][T3]

There has been a significant amount of research in developing analysis and design tools based on passivity and dissipativity theory for systems with continuous dynamics. However, many systems of interest in CPS cannot be described by the common ODE nonlinear models. For instance, there are systems whose dynamics evolves with the occurrence of events which may be irregular in time. These are described by discrete event systems (DES). The event driven evolution of these systems prohibits the application of traditional definitions of dissipativity. In [11], we present a notion of dissipativity for DES. We specialize this to DES described as finite automaton. Our work in [12] shows that dissipativity is both necessary and sufficient for some desired behaviours of a DES, such as invariance with respect to a set of states and stability of limit cycle.

The interaction of continuous and discrete dynamics in a CPS gives rise to hybrid behavior, a simple case is switching dynamics. A definition of dissipative switched systems is provided in [13] where we establish a relationship between the dissipativity and stability of a switched system. We also propose conditions under which the interconnection of dissipative switched systems in stable. In [14] and [T3], we generalize the concept of passivity indices to switched systems. This allows us to develop passivation methods for switched systems based on their passivity levels. More on this is discussed in chapter 7.

While a switched system model requires for the state to remain continuous when the dynamics switches between various modes, a more general framework is offered by hybrid models such as hybrid input output automaton (abbreviated as hybrid I/O automaton). These models contain both continuous states and discrete modes. A larger class of systems can be modeled using hybrid I/O automaton as it allows for a countably finite number of discontinuous jumps in the system state. Though there has been some work in the dissipativity of hybrid systems, most of these results focused on the special case of switched systems. We introduce a definition of dissipativity for systems modeled as hybrid I/O automata in [15][T2]. We specialize this definition to useful notions of QSR-dissipativity and passivity and show that the preliminary results on stability and compositionality of traditional dissipative systems hold for dissipative hybrid I/O automata as well. Further, our work in [12] discusses several important developments in dissipativity based approaches for hybrid systems. We also provide significant insights into dissipativity theory of hybrid I/O automata as an integrated platform for control design of heterogeneous systems such as continuous dynamical systems, DES, timed automata and switched system models.

Chapter 3

Passive Systems - Relationship with Positive Real and Conic Systems

References:[16][17][T4][T5]

Passivity is an energy-based property for nonlinear systems. Positive realness captures a similar property for linear time-invariant systems described by transfer functions. This connection exists in the literature. A detailed discussion on relationships between the various sub-classes of passive and positive real systems is provided in [16], [17], [T4] where we survey several important results and provide new conclusions to solidify the connection between passive and positive real systems. Conicity is another property modeling the input-output behavior of a system. In [T5], we show that passivity is intimately related to conic systems. We reinforce this connection via the concept of passivity indices, which allows us to use many classical results from conic systems theory. Building upon these discussions, [T5] also proposes the open-loop conditions that guarantee closed-loop stability of a feedback interconnection of two systems that are not necessarily passive or even stable. These results are generalized for the compositional verification of stability for switched systems.

Chapter 4

Computation of Passivity Indices

References:[18][19][T6-T8]

Passivity indices provide a measure of how close or far a system is from being non-passive. The importance of passivity indices in control design has been well studied (for more details see chapter 7). Besides the standard results on feedback and parallel interconnection of passive systems discussed in subsection 1.4.1, our work in [18] and [T6] discusses the passivity of cascade connections of passive systems. In [18], we propose an approach to infer the passivity levels (indices) of the cascade interconnection of systems which may or may not be passive. We also establish a technique for the design of output feedback controllers to ensure the passivity of this cascade interconnection. Note that to employ the majority of these passivity based control design techniques, we need to know the passivity levels of the system under consideration. In the remaining part of this chapter we will briefly outline our work on two main methods - analytical and experimental, for the computation of passivity indices.

4.1 Analytical Methods

References: [19][T7]

In control systems theory, linear time-invariant systems form an important class of systems with a wide range of applications. In linear systems theory, it is possible to formulate several system properties in the form of linear inequalities. The use of linear matrix inequalities (LMIs) in passivity theory comes from earlier work on the positive-real lemma, also known as the KYP Lemma. This lemma was developed by Kalman using results from Yakubovich and Popov. The lemma has been extended to nonlinear systems. In [T7], LMI conditions are presented to check passivity and QSR-dissipativity of linear systems, both for continuous and discrete time cases.

Moreover, in [T7], we present a sum of squares method to assess passivity of nonlinear systems. The nonlinear systems of interest are ones with only polynomial terms. Examples of polynomial systems can be found in applications such as biological systems and process control. The original non-negativity conditions for dissipativity inequality are relaxed as sum of squares (SOS) conditions, and once the problem is formulated this way, there are efficient solvers to find a solution. Like the other SOS problems, the existence of a SOS storage function is only sufficient for showing passivity. In general, it is not possible to use SOS methods to demonstrate that a system is not passive. SOS methods are also employed to find passivity indices of polynomial nonlinear systems. This idea is expanded in [19], [T7] to switched systems. SOS optimization methods are used to determine whether a switched system is dissipative. This is especially useful for switched systems where notions of dissipativity involve finding multiple storage functions. Examples and relevant software code are provided to illustrate these methods. SOS methods can be used to find both storage functions and cross supply rates. These methods can greatly reduce the effort required to demonstrate that a system is dissipative.

4.2 Experimental Determination

References: [T8]

In many applications, traditional system models described by differential equations may not be practical. This can be caused by a number of factors including nonlinear or time-varying dynamics that may not be modeled or logical components such as look-up tables that may not be described by either differential equation or logical models. For these systems alternative methods of determining passivity or dissipativity directly from input-output data may be used. The traditional method of control system design involves modeling the plant to be controlled, analyzing the plant, and then synthesizing a controller. Passivity based methods instead use the knowledge about passivity levels of a system for analysis and control design. In [T8], we present several methods to determine the passivity indices of a system. Besides the traditional analytical methods, we also formulate data-based experimental determination of passivity index. We show that given a sufficiently large data set of inputs and corresponding system response, it is possible to evaluate the passivity level of a system. The amount of data required for this is comparable to that required for a model verification. In particular, we consider an automotive system with adaptive cruise control algorithm, and formulate the problem of experimental or data based determination of passivity index as a numerical optimization problem which is solved using the Hooke and Jeeve's method. The results are verified against the simulations on CarSim, a virtual car platform.

Chapter 5

Local Passivity and Dissipativity in Nonlinear Systems

References:[20][21]

Passivity and dissipativity can be defined in the same way for linear systems and nonlinear systems; however, extra attention should be paid to special behaviors of nonlinear systems. Unlike linear systems, important properties of nonlinear systems, like stability, are typically studied in a neighborhood of an equilibrium point or other stationary sets and local analysis doesn't necessarily imply global stability. Local stability and region of convergence have been studied before using different techniques; however, local dissipativity and local passivity of nonlinear systems still requires more in-depth study. In [20], we focus on the local passivity and local passivity indices of nonlinear systems. An example in [20] demonstrates that a system which is passive in a local region around one equilibrium may loose its passivity around a different one. Another example shows that expanding the local region of study around an equilibrium can change the provable passivity index of the system.

Defining dissipativity properties in a local sense for nonlinear systems requires careful consideration of how we define the admissible control and how we restrict the state space. This has been addressed in the literature using different approaches and each has its own importance and applications. In [20], it is assumed that the input belongs to a particular set $\mathcal{U}$, and the states belong to $\mathcal{X}$, and any input from the set $\mathcal{U}$ applied to the system does not drive the states out of $\mathcal{X}$.

The idea in [20] is expanded by introducing optimization methods to study passivity of nonlinear systems and to find passivity indices over a subset of state and input space. System's dynamics are considered to be defined by polynomial functions, and state space and input space are semi-algebraic set.

Proving passivity and dissipativity, just like stability and similar concepts, depends on finding a (so-called) Lyapunov functional. However, there are no general systematic methods to find such Lyapunov functionals. Though for some special electrical or mechanical systems, energy functions can act as Lyapunov functionals, it is basically a matter of trial and error. Several attempts have been made to develop systematic approaches to find Lyapunov functional for particular classes of systems, like linear systems, or nonlinear systems with polynomial fields, but a general methodology is still lacking. This paper addresses this gap by providing ways to find Lyapunov functionals through approximations, with an emphasis on dissipativity applications.

Even though many nonlinear systems are described by differential equations in polynomial form, there are many cases where the functions are not polynomial. One way to study such systems is through approximations by simpler models. In [21], we propose approximations through multivariate polynomial functions. The methodology presented gives us approximate models, along with error bounds in a well-defined neighborhood of an operating point. Central to this approximation is *the Stone-Weierstrass approximation theorem,* which states that under certain circumstances, any real-valued continuous function can be approximated by a polynomial function as closely as desired. Two different methods to approximate a nonlinear function have been employed here. The first methodology is Taylor's Theorem, which gives a polynomial approximation and bounds on the function. However, finding error bounds in this method requires significant amount of calculations, and results in large optimization problems in real world applications. The second approximation method is through Multivariate Bernstein Polynomials with simpler calculations that lead to a more tractable optimization problem. Several results are given to test both local stability and local dissipativity of a nonlinear system through sum of squares optimization and polynomial approximation of the system. Local QSR-dissipativity of the system, local passivity, and local passivity indices are also derived from the dissipativity results.

Further discussion on determining dissipativity of a system based on its approximation can be found in chapter 6.

Chapter 6

Passivity and Dissipativity of a System and its Approximation

References:[22]–[27][T9-T11]

6.1 Linearization of Nonlinear and Switched Systems

References:[22], [23][T9]

The goal of this research is to investigate what passivity properties for a nonlinear system can be inferred when its linearization is known to be passive. For a nonlinear system which is completely reachable and passive, its linearization remains passive [4]. We explore the converse problem of studying passivity for a nonlinear system through its linearization in [22], [T9]. This is of practical importance because many of the controller designs for nonlinear systems are based on their linearized models. It also allows to take advantage of the well-established passivity theory for linear systems.

We consider both continuous-time and discrete-time systems with feed-through terms. Our main results show that when the linearized model is simultaneously strict passive and strict input passive, the nonlinear system is passive as well but within a neighborhood of the equilibrium point around which the linearization is done [22]. The results generalize to the case when the linearization is QSR-dissipative. In particular, we establish conditions under which the passivity indices of the linearized models are equivalent to those of the nonlinear systems around the equilibrium point.

We show that merely strict passivity for the linearized models may not be sufficient to guarantee local passivity of the nonlinear systems with feed-through terms [T9] but it is important for the linearization to be ISP as well. This is particularly relevant for discrete-time systems since the feed-through terms are necessary to show passivity of the system. One set of sufficient conditions are established to guarantee local passivity of the nonlinear system when the linearization is strict passive. When the feed-through term is zero, our results reduce to the previous results.

We extend a subset of these results to passive switched systems as well. In [23] we consider switched nonlinear systems whose modes share a common equilibrium. We can linearize each mode of the switched system around this equilibrium to obtain a linearized approximation of the switched nonlinear system. We show that if this linearized switched system is both strictly passive and input passive (SSIP), then the switched nonlinear system is locally passive in the neighborhood of equilibrium. This result helps us address the passivity of a larger class of systems. Since control for systems is often designed by linearizing them, these results are of practical use for not just for analysis but also for passivity based control design.

6.2 Discretization and Quantization of Nonlinear Systems

References:[24]

Passivity theory has been applied to a wide variety of continuous systems. However, when these passive systems are subject to the effects of a digital interface then in general, there are no guarantees for the digital system to be passive. Several preliminary results show that passivity is not preserved under discretization, which means the discretized system may not be passive even if the original continuous-time system is passive. In addition to discretization, the effect of quantization also needs to be considered when digital controllers interact with the environment by means of analog-to-digital converters or digital-to-analog converters that have a finite resolution. Moreover, quantization is necessary when the information between plants and controllers is transmitted through communication networks. In [24], we focus on the techniques that are required to ensure passivity of a nonlinear quantized system. The main contributions of this work are (i) the derivation of conditions guaranteeing the passive structure of an OSP system under quantization, and (ii) its application in ensuring stability of a passive switched systems with passive quantizers. Additionally, we propose an input-output transformation block for the OSP system. The passivity levels of the system with respect to transformed input-output pair is same as the passivity level of original OSP system. We show that when the system is interfaced with a passive quantizer via this input-output transformation block, then the system with quantized inputs and outputs is still passive. This is an important result in developing passivity as a control design tool for CPS which often involve a tight interaction of continuous and digital dynamics.

6.3 Approximately Input-Output Similar Abstractions

References:[25][T10]

Another set of approximate system models is obtained via the theory of simulation and bisimulation (A. Girard, and G. J. Pappas, Approximation Metrics for Discrete and Continuous Systems, in IEEE Transactions on Automatic Control, vol. 52, no. 5, pp. 782-798, May 2007.). These models, referred to as abstractions, are used to obtain a finite symbolic model representation of systems. A symbolic abstraction of system can be used in designing control for temporal logic specifications or analyzing the interaction between a system and a software. Our work in [25] and [T10] focuses on the invariance of dissipativity properties of a system and its symbolic abstraction. In particular, we discuss the QSR-dissipativity of system abstractions obtained using approximate input-output simulation relation. We formulate relationships to infer the QSR-dissipativity of a system from its particular abstract models and vice-versa. We demonstrate the use of these results in two scenarios, (i) guaranteeing the performance (in terms of passivity levels) of digital implementation of a control system and (ii) compositional verification of safe operation of a closed loop system consisting of a continuous dynamics plant and a software controller. Here, by safe operation we mean that the closed loop is passive. As a future direction, the results in [25] can provide the basis for a joint control design technique to meet both, temporal logic and more traditional stability and passivity specifications.

6.4 A General Class of Approximate Systems

References:[26][27][T11]

In this section we discuss the research carried out to investigate the passivity of a system as inferred from studying an approximate model of its dynamical behavior. In a large scale CPS, precise knowledge of the mathematical model will be difficult to obtain. Moreover for design and analysis purposes, it is sometimes beneficial to consider an approximation of the system. We establish relationships between dissiptivity properties of two mathematical models, one of which could represent accurately a physical system and the other could represent an approximation. Of course, the two mathematical models can represent two different approximations of the same physical system as well. We consider the setup where the error between the outputs of the two models is bounded or small in a suitable sense.

Our results in [26], [27] and [T11] show that an excess of passivity (whether in the form of ISP, OSP or VSP) in the approximate model guarantees a certain passivity index for the system, provided that the norm of the error between the two models is sufficiently small in a suitably defined sense. Further, we consider QSR–dissipative systems and show that QSR-dissipativity has a similar robustness property, even though the supply rates for the system and its approximation may be different. We apply our results to particular approximation methods, such as linearization of a nonlinear system around an equilibrium point, model reduction of a higher-order system to obtain a lower-order model, sampled-data systems and quantization, and to polynomial approximations of a nonlinear system around an equilibrium.

Chapter 7

Passivation

References:[14][23][28]–[33]

A major part of control design based on passivity theory assumes passivity of the system under consideration. However, many physical systems are not inherently passive; and passivity may not be preserved when the control algorithms are implemented in software even if the controllers are designed to be passive. The goal of this research is to develop control design methods to guarantee both the passivity and performance. This procedure of ensuring passive system behavior through controls is called passivation. In this chapter we present an overview of control methods proposed by our research group, to passivate a wide class of dynamical systems.

7.1 Passivation using Passivity Indices

References:[28]

Passivity indices are used to measure the excess or shortage of passivity. While most of the work in the literature focuses on stability conditions for interconnected systems using passivity indices, in our work we focus on the passivity and passivation of the feedback interconnection of two IF-OFP systems. Although it is well known that the negative feedback interconnection of two passive systems is still passive, the quantitative characterization of passivity for the closed-loop system was not addressed previously. In [28], we propose a measure of passivity indices for the negative feedback interconnection of two input feed-forward output-feedback (IF-OF) passive systems. The two systems need to be neither passive nor linear in general. It is shown that passivity, with respect to the full input and output, may be reinforced under feedback interconnection. We also consider the problem of partial passivation where we present conditions under which passivity for a desired input and output pair can be guaranteed. Closed form expressions for a measure of passivity indices of the closed loop system are also established.

7.2 Passivation of Nonlinear Systems using M-Matrix

References:[29]–[31]

The well-known methods for passivation methods use series, feedback, or feed-forward controllers to passivate a system. However, the use of any of these methods may constrain the class of systems where the passivation method may be applied. For example, feedback passivation alone cannot passivate systems that are non-minimum phase or have relative degree larger than one. In [29]–[31], we introduce a passivation method using an input-output transformation matrix. We refer to this matrix as M-matrix. It represents a combination of the series, feedback and feed-forward interconnections for passivation. This passivation method can be applied to any finite gain stable system and so the constraints imposed by passivation using feedback alone are removed. In particular, the passivation method can passivate systems with input-output delays, such as chemical systems and can be applied to human operators acting as controllers. We show that by appropriately designing the passivation parameters, desired passivity levels and stability for the system can be guaranteed. Moreover, the system after passivation can be used as a controller to stabilize or passivate another plant.

In order to satisfy certain performance requirements, the passivation parameters can be selected by solving an optimization problem, such as minimizing the tracking error. If the relation between the objective function and the passivation parameters are known, then the optimization problem can be solved using a gradient-based method. However, if such a relation is expensive to obtain or difficult to analyze, then a non-gradient based method can be used. For example, if the dynamics for the plant are unknown, then we can measure the system performance via computer simulations (i.e. using a co-simulation framework) and search for the passivation parameters according to the method of Hooke and Jeeves. It has also been shown that we can use transfer functions in our passivation method which allows more flexibility in selecting the parameters in order to meet performance specifications.

We apply the M-matrix passivation method to adaptive cruise control design for automotive systems. An important issue we consider is that when the control algorithm such as a PID controller is implemented in software, a time-delay is induced. The time-delay may be due to accumulating brake or engine actuation lags, signal processing delay, sensor measurement delay or interactions between different control algorithms. We consider both the case when the control action is performed by a human operator and the case when the control algorithm is simply a PID controller but contains a time-delay. The experimental results in CarSim and Simulink demonstrate that our passivation approach can guarantee not only stability but also good tracking performance for both cases.

7.3 Passivation of Switched Systems

References:[14][23][32][33]

Passivation of switched systems using passivity indices was considered in [14]. In [32], we consider the passivation of a switched system consisting of a non-passive switched controller in a feedback interconnection with a passive plant. We generalize the M-matrix method discussed in previous section to a switched M-matrix. The basic idea behind this approach is to introduce an input-output transformation matrix for every non-passive subsystem. The transformation parameters for all the subsystems are designed jointly to ensure passivity of the resulting closed loop system. We further extend these results to IFP and OFP switched controllers. An improvement over this passivation technique is proposed in [33]. While [32] designs separate M-matrices for each non-passive subsystem of the switched system, in [33] we propose an enhancement where a single input-output transformation is sufficient to passivate the switched system. Since multiple passivating matrices are now replaced by a single transformation, this method significantly reduces the design and implementation cost of passivating controllers.

Passivating method based on M-matrix or switched M-matrix requires us to compute the L_2-gain of the system. An alternative approach is considered in [23] where we propose an LMI based passivating control for systems that can be modeled as switched dynamical systems. Typical control design approaches for switched systems (without stability assumptions), use nonlinear controllers that are difficult to synthesize and are valid only for specific classes of systems with known switching sequences. In many large scale infrastructure systems this switching sequence is a function of variable that cannot be predetermined. For example, in the power grid with tight integration of renewables, renewable inputs like wind speed and solar intensity vary continuously. Depending on the availability, renewables either participate or do not participate in the network, and hence switching dynamics are inherent. In [23], we propose a control design scheme to ensure passivity of such switched systems under arbitrary switching sequences. The key contribution of this work is the synthesis of passivating controllers for nonlinear switched systems using linear approximations. We show that the state strictly input passivity of the linear approximation ensures passivity of the original nonlinear system. This allows us to formulate the passivating controller as the solution to a system of linear matrix inequalities (as opposed to the typical nonlinear matrix inequalities encountered in switched systems literature), that can readily be solved using open source solvers. This is significant, as it allows us to synthesize controllers for nonlinear switched systems in a computationally efficient manner. We demonstrate the effectiveness of this design on a standard IEEE test power system with renewables.

Chapter 8

Dissipative Synthesis of Large-Scale Systems with Symmetry

References:[34]–[36]

In dynamical systems theory, especially large scale applications, symmetry of interconnections of sub-systems is a desirable property. The presence of symmetry in a large scale system can often simplify the control design and analysis tasks. In several engineered systems such as multi-agent systems, if the system can be decomposed into interconnection of lower dimensional symmetric systems, then this can provide some useful insights into the dynamical behavior of the interconnected system in a computationally efficient manner. The existence of symmetry here means that the system dynamics are invariant under transformations of coordinates. Our work in this direction has been along the following lines.

8.1 Stability Conditions using Symmetry and Dissipativity

References:[34][35]

In our work, stability conditions for large-scale systems are derived by categorizing agents into symmetry groups and applying local control laws under limited interconnections with neighbors [34]. When subsystems of a symmetric system are dissipative, overall stability properties can be studied. We derive conditions to calculate the maximum number of subsystems that may be added while preserving QSR-dissipativity and stability of the interconnection. These results may be used in the synthesis of large-scale systems with symmetric interconnections [35].

Other work on distributed systems for this project is in exploiting communication symmetries in networked dissipative systems to show stability [34]. In cyclic and star-shaped symmetric systems, we do not place any restrictions on the dynamics of systems which may actually be different. The form of the symmetry can be used together with the dissipativity property of agents to simplify the conditions that guarantee stability of a distributed system. The results are robust under parameter variations and apply to systems with heterogeneous dynamics too, as long as all the systems satisfy the same dissipativity inequalities.

8.2 Passivity Indices in Symmetric Interconnections

References:[36]

Passivity indices can be used for interconnections of agents to assess the level of passivity. Motivated by the interest of sufficient stability conditions in [34], we derive the passivity indices for both linear and nonlinear multi-agent systems with symmetry in [36]. For linear systems, we can explicitly calculate the passivity indices whereas in the nonlinear case, passivity indices are characterized by a set of matrix inequalities. We also focus on symmetric interconnections and specialize stability results to this case, with extensions of network delays. Normally dissipativity and passivity cannot be preserved if random delays are introduced into the network. Scattering transformations are used to force the energy stored in the delayed network to be non-negative. It therefore preserves the stability results with updated output feedback passivity index.

Chapter 9

Dissipativity in Networked Control Systems

References:[15][24][37]–[50][T12-T20]

9.1 Networked Control Systems

References:[15][24][37][38][T12][T13]

In this research, work has been done to address fundamental problems caused by network effects including quantization [24], packet loss [37], [T12], [T13], communication delays [15], [38], and limited bandwidth. We know that when two passive systems are connected in feedback or parallel interconnection then passivity is preserved for the resulting interconnected system. However, in presence of these network effects, there is no such guarantee.

When quantization is present, as is the case with digital controllers or communication channels, our work in [24] introduces a control framework under which passivity for switched and non-switched systems can be maintained. This framework is based on the use of an input-output coordinate transformation to recover the passivity property.

In [37] and [T13], we analyze passivity for a class of discrete-time switched nonlinear systems that switch between two modes - an uncontrolled mode in which the system evolves open loop, and a controlled mode in which a control input is applied to the system. Such a model has recently been used for a network controlled system in the presence of packet drops introduced by a communication channel. We show that if the ratio of the time steps for which the system evolves open loop versus the time steps for which the system evolves closed loop is bounded below a critical ratio, then the nonlinear system is locally passive in this sense.

The effect of communication delays on the passivity of networked switched systems is considered in [38]. When two switched systems connected in negative feedback, communicate over a network with time delays, the non-passive nature of the delay network can disrupt the passivity of the interconnection. We show that by the introduction of a wave variable transform (WVT) unit at both ends of the communication channel, one can guarantee the passivity of this networked system. A modified WVT approach can be used to tackle time-varying delays. In [15] we extend this framework to hybrid systems. This allows to discuss about the networked interconnection of a much larger class of dynamical systems.

9.2 Event Triggered Control and Estimation

References:[39]–[48][T14-T20]

In a typical event-based feedback control system, the control signals are kept constant until the violation of an event triggering condition on certain signals which triggers the re-computation of the control actions. Compared to time-driven control where constant sampling period is applied to guarantee stability in the worst case scenario, the possibility of reducing the number of computations and thus of transmissions, while guaranteeing desired levels of performance makes event-based control very appealing in networked control systems (NCSs). We have contributed several important results in this area.

In [39]–[41], [T16], [T18] and [T19] the stability conditions for an event-triggered networked system based on the passivity properties of sub-systems have been explored. These works mainly focus on passivity and passivation of event-triggered feedback interconnected systems of two IF-OFP systems. Passivity indices are used to measure the excess or shortage of passivity. It is shown that passivity indices of continuous feedback systems can be determined from the passivity levels of individual subsystems. The passivation conditions to render a nonpassive plant passive are also obtained based on passivity indices. The results can be viewed as the extension of the well-known compositional property of passivity. We first derive the conditions to characterize passivity indices for the interconnected systems. The event-triggering condition proposed guarantees that these indices can be achieved. Then the passivation problem is considered and passivation conditions are provided. The passivation conditions depend on the passivity indices of the plant and controller and also the event-triggering condition. This reveals the trade off between desired passivity levels and communication resource utilization.

Compositional control methods are well-suited for the design of large-scale control systems. QSR-Dissipativity and passivity are closely related to stability and may be utilized to show Lyapunov and finite-gain stability for dynamical systems under certain conditions. Additionally, passivity is preserved under feedback and parallel interconnections of passive systems and may be utilized to build larger stable systems. In [42], [43] and [T14], we show that the dissipativity and passivity based control combined with event-triggered networked control systems (NCS) provide a powerful platform for designing CPS. We propose QSR-dissipativity, passivity and finite-gain L2-stability conditions for an event-triggered NCS in cases where an input-output event-triggering sampler condition is located on the plants output side, controllers output side, or both sides leading to a considerable decrease in communication load amongst sub-units in NCS. We show that the passivity and stability conditions depend on passivity levels for the plant and controller. The results also illustrate the trade-off among passivity levels, stable performance, and systems dependence on the rate of communication between the plant and controller. Further, the output-based triggering conditions introduced in these works are easy to design and understand. The main motivation behind these works is that by designing and connecting individual stable passive event-triggered NCSs with desired passivity levels, one can design larger stable passive compositional networked systems that are suitable for the design and control of large-scale systems such as CPS.

In [44], we consider state estimation for multiple plants across a shared communication network. Each linear time-invariant plant transmits information through the common network according to either a time-triggered or an event-triggered rule. For an event-triggered algorithm with carrier sense multiple access (CSMA), each plant is assumed to access the network based on a priority mechanism. For a time-triggered algorithm combined with time division multiple access (TDMA), each plant uses the network according to a schedule that is decided a priori. Performance in terms of the communication frequency and the estimation error covariance is analytically characterized for event-triggered schemes. Using these characterizations, we show that event-triggered schemes may perform worse than time-triggered schemes when the effect of the communication network is explicitly considered.

[45] is focused on the formation control problem of networked passive systems with event-driven communication. We derive a triggering condition to achieve distance-based formation among the agents with an ideal network model being assumed; [46] and [T17] study the quantized output synchronization problem of networked passive systems with event-driven communication, and proposes an event-driven communication strategy such that output synchronization errors of the networked passive systems are bounded by the quantization errors of the signals transmitted in the communication network. We then consider the case when there are constant network induced delays between coupled agents [47]. The effects of network induced delays are considered. In this paper, a framework for output feedback based event-triggered NCS is introduced. The triggering condition is derived based on passivity theorem which allows us to characterize a large class of output feedback stabilizing controllers. The proposed set-up enables us to consider network induced delays both from the plant to the network controller and from the network controller to the plant. Additionally, the effects of quantization of the transmitted signals in the communication network are taken into consideration and conditions for finite-gain L2 stability are achieved in the presence of time-varying (or constant) network induced delays with bounded jitters, without requiring that the network induced delays are upper bounded by the inter-event time.

Finally, in [48] and [T15], we introduce a design framework for event-triggered networked control systems based on passivity. We consider the effects of network induced time-delays, signal quantization and data loss in communication links between the plant and controller and show $\mathcal{L}_2$-stability and robustness for the control design. We introduce simple asynchronous triggering conditions that do not rely on the exact knowledge of the systems dynamics and are located on both sides of the communication network. This leads to a great decrease in the communication rate between systems. Additionally, we establish lower-bounds on inter-event time intervals for the triggering conditions and characterize the design's robustness against external disturbances. We illustrate the relationship amongst stability, robustness and passivity levels of plant and controller. Moreover, we analyze the designs robustness against packet dropouts. Lastly, we calculate the passivity levels for the entire event-triggered networked control system. This is beneficial in design of compositional NCS. The results are design-oriented. By following the proposed framework, the designer can characterize clear trade-offs amongst passivity levels, design parameters, time-delays, effects of signal quantization and triggering conditions, stability, robustness and performance and make design decisions accordingly.

9.3 Multi-Agent Systems

References:[49][50][T20]

In [49] and [T20], we study the output synchronization problem of networked passive systems with event-driven communication, in which the information exchange among the coupled agents are event-based rather than pre-scheduled periodically. We propose a setup for the interconnected agents to achieve output synchronization with event-driven communication in the presence of constant communication delays. The results presented in this work are important extensions of applying event-driven communication to control of multi-agent systems, especially when it is difficult to derive a common upper bound on the admissible network induced delays, or when the network induced delays between coupled agents are larger than the inter-event time implicitly determined by the event-triggering condition.

In [50], we study the synchronization of a group of output passive agents that communicate with each other according to an underlying communication graph. A distributed event-triggered control framework that guarantees synchronization and reduces the required communication rate is introduced. A general Byzantine attack on a multi-agent system is defined and its negative effects on synchronization are characterized. The Byzantine agents are able to intelligently falsify their data and manipulate the underlying communication graph by altering their control feedback weights. Next, a decentralized decision making and detection framework is introduced and its steady-state and transient performances are analyzed. Further, a method of identifying Byzantine neighbors and a learning-based procedure for estimating the attack parameters are introduced. Lastly, learning-based control frameworks to mitigate the effects of the attack are proposed.

Chapter 10

Application of Passivity Theory to Automotive Systems

References:[31][51][T21-T23]

In chapter 7, we discussed a passivation based on an input-output transformation known as M-matrix. The parameters of M-matrix can be chosen from a set of values satisfying certain inequalities. One of the ways to select the passivation parameters is by solving an optimization problem such as minimizing the tracking error. As an application of this passivation method, we consider systems with input-output time delays [31], [T21]. In particular, we consider automotive systems where time-delays are unavoidable due to the software implementation of control algorithms. We show that M-matrix based passivation method can be used to compensate for the time-delay in the controller and improve the closed-loop system performance. To validate this result, we provide simulation results in CarSim and Simulink; the optimization method used in [T22] is called Hooke and Jeeves' method. This is a non-derivative numerical optimization scheme. The advantage of this method is that it only requires the values of objective function but it does need any derivative information.

In [51] and [T23], we modify the above scheme to include extremum-seeking, an online optimization method. As compared to the previous work with Hooke and Jeeves optimization method, extremum-seeking control performs faster and requires only one experiment to achieve the optimal values. This decreases the time to find correct passivation parameters from almost a quarter of an hour to seconds depending on the length of experiment. Some of other advantages of extremum-seeking control (ESC) compared to Hooke and Jeeves' method are ESC's better robustness against disturbance and noise, and its relatively less sensitive overall structure towards sudden changes. Additionally, extremum-seeking controller optimizes the system in real time. We apply our results to an adaptive cruise control system and analyze the systems performance under the given extremum-seeking based co-simulation framework. Our experiments show that one does not necessarily need to know the motion profile of the tracking target in advance. The controller parameters can instead be tuned on-line. We satisfactorily test the performance of our controlled designed for a certain tracking profile against different speed trajectories.

Chapter 11

Dissipativity Based Robust Nonlinear Model Predictive Control

References:[10][52]

Model predictive control (MPC) is an effective control technique to deal with multi-variable constrained control problems and it has been widely adopted in a variety of industrial applications. The success of MPC can be attributed to its effective computational control algorithm and its ability to impose various constrains when optimizing the plant behavior. Unlike the conventional feedback control, MPC first computes an open-loop optimal control trajectory by using an explicit model over a specified prediction horizon, initial parts of thus calculated control trajectory is actually implemented and the entire process is repeated for the following prediction intervals. Although MPC has many advantages, several issues such as feasibility, closed-loop stability, non-linearity and robustness still need to be studied.

In [10] and [52], we derive a robust stabilizing output feedback nonlinear MPC (NMPC) scheme by using passivity and dissipativity. Instead of assuming that both the nominal model and the plant are passive systems with the same dynamics, we assume that the model for prediction and the actual plant dynamics are dissipative and that their dynamics can be different from each other. This is more general than passivity and allows for systems to be even non-passive. We characterize the model discrepancy between the nominal model and the real system by comparing the outputs for the same excitation function. With this characterization of model discrepancy, we are able to compare the supply rate between the nominal model and the real system based on their passivity indices. Then, by introducing specific stabilizing constraint into the MPC based on the passivity indices of the nominal model, we show that the control input calculated using the nominal model can guarantee stability of the plant to be controlled.

Chapter 12

Passivity Applied to Euler-Lagrange Systems with Nonholonomic Constraints

References:[53][T24]

One intended application of passivity in this project is the control of networked Euler-Lagrange (EL) systems. Such systems include many mechanical systems such as robotic manipulators and mobile robots. Passivity applied to EL systems has been well studied. However, past research has typically ignored nonholonomic constraints in these systems. However, many systems have these constraints. For example, actual wheeled vehicles have a minimum turning radius. The result is that the state of a vehicle depends on the path taken to achieve it. These constraints on the vehicles position and velocity are nonholonomic, so a more complex model must be used. When these constraints are considered, the dynamics of the system are much more realistic. In [53] and [T24], we consider a network of such vehicles, each with EL dynamics and nonholonomic constraints and propose a new setup, which allows for passivity to be used as the design and analysis tool of EL systems despite the added constraints.

The general problem in [53] starts with a vehicle described by EL equations with constraints. First a local state feedback is applied and the coordinate frame is redefined in order to achieve a simplified model. This simplified model is then input-output linearized to derive a model that is a simple double integrator from the input-output perspective. With one last local control applied, the vehicle dynamics are made locally passive despite the nonholonomic constraints. A network of these agents is then connected over a fixed topology, specified by a graph Laplacian. At this point, a complete feedback loop is derived. This feedback loop can be appropriately subdivided to look like the interconnection of two passive systems. The feedback invariance that passivity provides allows for the stability of the loop to be inferred immediately.

We further extend the results of [53] by considering delays in the communication between agents. A wave variable transformation block is introduced to preserve the passivity of the interconnection despite the time-varying delays. This proposed setup solves the problem of output synchronization of networked EL systems subject to nonholonomic constraints and communication restrictions.

Chapter 13

Dissipativity-Based Certificates for Reliable Stabilization of Multi-Channel Systems

References:[54]–[62][T25]

The goal of this research is to develop new theory, algorithms, and demonstrations related to stabilization of multi-channel systems using dissipativity-based certifications and optimization theory. The main goal is reliable stabilization, i.e., the system remains stable (or additionally satisfies some performance guarantee) even if some components fail. Our work in this direction is along the following lines.

13.1 Reliable Stabilization using Dilated LMIs

References: [54]–[60]

The first area of this work is in reliable stabilization via rectangular dilated LMIs and dissipativity-based certifications [54]–[56]. This is a design framework for reliable stabilization of multi-channel systems developed based on a set of rectangular dilated LMIs and dissipativity certifications. We provide stabilization results that are less conservative than those existing in the literature. Further, we extend the stability condition for an additive model perturbation in the system. Moreover, the framework in which we have defined the problem provides a computationally tractable treatment for handling the issue of robust/reliable stabilization and model uncertainty. For instance, in [57], we use a rectangular dilated LMIs framework to provide a relaxed sufficient condition for the simultaneous stability of a multi-channel system both when all of the controllers work together and when one of the controllers ceases to function due to a failure. More recently, we extended this design framework to the problem of reliable stabilization for N MIMO systems when some of the shared controllers among these systems are faulty, in the sense that they fail to operate properly due to subsystem (module) failures that may occur in actuators, sensors or controllers [58]. Moreover, a sufficient condition for the solvability of such a problem is given in terms of a minimum-phase condition of each subsystem and a lower-bounding condition on the number of outputs of each channel.

13.2 Game-Theoretic Tools for Robust Stabilization

References: [59][60][T25]

Another area of this research is in studying feedback Nash equilibria for multi-channel systems via a set of non-fragile stabilizing state-feedback solutions and dissipativity inequalities [59], [60]. This problem of state-feedback stabilization for a multi-channel system is considered in the framework of differential games, where the class of admissible strategies for the players is induced from a solution set of the objective functions that are realized through certain dissipativity inequalities. In such a scenario, we characterize the feedback Nash equilibria via a set of non-fragile stabilizing state-feedback gains corresponding to constrained dissipativity problems. Moreover, we show that the existence of a near-optimal solution to the constrained dissipativity problem is a sufficient condition for the existence of a feedback Nash equilibrium, with the latter having a nice property of strong time consistency.

Related work is on robust feedback Nash equilibrium for multi-channel systems via differential games and a class of unknown disturbance observers [T25]. Again the problem of state-feedback stabilization for a multi-channel system is cast in a differential-game theoretic framework. We specifically present a sufficient condition for the existence of a robust feedback Nash equilibrium, where each agent aims to optimize different types of objective functions and when agents may unaware of all aspects or the structure of the game. We characterize the robust feedback Nash equilibrium solutions via a set of relaxed LMIs conditions and concepts from a geometric control theory, namely, a class of decentralized unknown disturbance observers where the latter are used for the game with an incomplete information.

13.3 Robustness against Attacks

References: [55][61][62]

In CPS, the strong dependence on the cyber infrastructure in the overall system increases the risk of cyber attacks and jeopardizes system performance. A related problem is that of ensuring reliability when the faults arise due to adversaries that are trying to strategically harm the control objective. We consider the problem of ensuring stability in the face of an adversary that poses a Denial-of-Service attack on the control packets [55], [61]. By assuming a Markov modulated attack, we provide the optimal controller design to defend against such an attack.

In [62], we further consider a data injection attack on a CPS. We propose a hybrid framework for detecting the presence of an attack and operating the plant in spite of the attack. Our method uses an observer-based detection mechanism and a passivity balance defense framework in the hybrid architecture. By switching the controller, passivity and exponential stability are established under the proposed framework.

Chapter 14

Model-Based Networked Control

References:[63]–[88][T26-T29]

Model-based networked control systems (MB-NCS) use an explicit model of the plant, in the controller, in order to reduce the network traffic while attempting to prevent excessive performance degradation. Intermittent feedback consists of the loop remaining closed for some time interval, then open for another interval. MB-NCS were introduced in [63], [64], [T29]. Our work in this direction provides a set of results in stability of model-based networked control systems with intermittent feedback, which we intend will serve as a nexus between the study of systems with instantaneous feedback and with continuous feedback.

In a MB-NCS, knowledge of the plant dynamics can be used to reduce the usage of the time-varying communication network. In [65]–[67], necessary and sufficient conditions for stability are derived as simple eigenvalue tests of a well-structured test matrix, constructed in terms of the update time, and the parameters of the plant and of its model. The effect of quantization in MB-NCS framework is considered in [68], [69].

We design error events in [70] based on the quantized variables. The use of these error events yields asymptotic stability compared to similar results in event-triggered control that consider non-quantized measurements such that stability conditions presented are given only in terms of the parameters of the nominal model and some bounds in the model uncertainties. We then study the stochastic stability properties of certain networked control systems under time-varying communication. Model knowledge is used to reduce the number of packet exchanges and thus the network traffic. Then stability performance-related aspects for plants in a networked control setting, employing MB-NCS with intermittent feedback is addressed in [71] and [72]. A lifting process is applied to a general MB-NCS configuration in which the controller is connected to the actuator and plant by means of a digital communication network resulting in a multi-rate system [73], [T28] .Online identification of system parameters in state space representation is used to upgrade the model and the controller under MB-NCS framework in [74]. In [75] and [T27], MB-NCS scheme is used to reduce communication to free up network resources for other applications. Furthermore, a model-based scheduling strategy is introduced in [76] to achieve ultimate boundedness stability in the sensor-actuator networked control systems, where an estimator and a nominal model of the plant are used explicitly at the controller node to generate control action and schedule control action updates.

We have also worked on combining the two important control techniques, MB-NCS and event-triggered control, for reducing communication traffic in control networks. The resulting framework is used for stabilization of uncertain dynamical systems and is extended to systems subject to quantization and time-varying network delays, see [77] and [78]. A necessary and sufficient conditions for stability for the case of large delays is developed in [77]. The use of a model of the plant in the controller node not only generalizes the zero-order-hold (ZOH) implementation in traditional event-triggered control schemes but it also provides stability thresholds that are robust to model uncertainties, see [79] [80]. This framework is then extended to the case where the controller and the events are designed in a decentralized manner [81], [82], [T26]. In addition to this, a practical alternative for the implementation of MB-NCS with intermittent feedback is developed in [83]. Design of optimal controllers for uncertain linear systems subject to communication constraints is investigated in [84]. Moreover, [85] presents a model-based event-triggered (MB-ET) control framework for stabilization of networked systems. The controller and the events are designed in a decentralized manner, based only on local information. This framework allows for considerable reduction of bandwidth since every agent broadcasts its local information to other agents only when it is necessary, based on the difference between real and estimated variables. Besides, the proposed decentralized event-triggered control technique in [86] guarantees that the inter-event times for each agent are strictly positive. Finally, the ideas in this note are used to consider the practical scenario where agents are able to exchange only quantized measurements of their states. In addition, our goal in [87] is to decrease the rate at which a perturbed system needs to transmit feedback information to update its controller node while maintaining stability and disturbance rejection properties. [88] addresses the problem of output feedback stabilization of continuous-time networked systems that are also perturbed by persistent external disturbances. Stabilization of the output feedback networked system is achieved by means of event-triggered control strategies which reduce the number of feedback updates.

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