On Passivity of a Class of Discrete-Time Switched Nonlinear Systems

Yue Wang\textsuperscript{1}, Vijay Gupta\textsuperscript{2}, and Panos J. Antsaklis\textsuperscript{2}, Fellow, IEEE

\textsuperscript{1}Mechanical Engineering Department, Clemson University, Clemson, SC 29634 USA
\textsuperscript{2}Electrical Engineering Department, University of Notre Dame, Notre Dame, IN 46556 USA

This paper analyzes the passivity and feedback passivity of discrete-time switched nonlinear systems with both passive and nonpassive modes that are affine in the control input. When a nonpassive mode is active, the increase in storage function is not necessarily bounded by the energy supplied to the switched system at every time step. Therefore, a switched system with at least one nonpassive mode is defined to be nonpassive in the classical passivity theory. In this paper, we propose a framework to analyze the passivity of such switched systems in a more general sense. We consider switched nonlinear systems which are affine in the control input and may consist of passive, feedback passive modes and modes which can not be rendered passive using feedback. In the proposed framework, we prove that a switched nonlinear system is locally feedback passive if and only if its zero dynamics are locally passive. A lower bound on the ratio of total activation time between (feedback) passive and non-feedback passive modes is obtained to guarantee passive zero dynamics. Finally, we prove that two important properties of classical passivity still hold for the proposed passivity definition. That is, 1) output feedback control can be used to stabilize the switched system, and 2) parallel and negative feedback interconnections of two such passive systems are also passive.

Index Terms—Generalized Passivity; Feedback Passivity; Switched Systems; Zero Dynamics; Discrete-Time Systems; Nonlinear Systems

I. INTRODUCTION

PASSIVITY is an important property of dynamical systems. Passive systems exhibit many desirable properties, e.g., i) the free dynamics and zero dynamics of passive systems are Lyapunov stable, ii) the parallel and negative feedback interconnections of passive systems remain passive, and iii) a passive system can achieve stability using output feedback [1], [2]. The classical definition of passivity [3]–[7] requires that the increase in a suitably defined storage function is bounded by the energy supplied to the system at every time step.

However, in many systems, this condition may be too restrictive. In [8], we considered a feedback passive system controlled across a communication network. In case of packet dropouts, there will be time steps at which the system evolves in open loop, and hence, the traditional passivity definition may be violated at those time steps. Thus, no matter how infrequently the packet drops occur, such a system will be termed nonpassive. In this circumstance, an integral version of the traditional definition of passivity may be more appropriate since this notion can allow the increase in storage function to be greater than the supplied energy if such instances happen with sufficiently low frequency. It was shown in [8] that the switched system is locally feedback passive if and only if its zero dynamics are locally passive under this notion of passivity.

However, the analysis in [8] relies on the system switching between two modes, with one mode being the open loop version of the other one. In this paper, we develop this concept further and consider switched systems with an arbitrary number of passive, feedback passive modes and modes which can not be rendered passive using feedback (non-feedback passive modes). For such systems, we provide a definition of passivity that reduces to the integral version of the traditional definition of passivity when the system has only one mode. However, for discrete-time switched nonlinear systems, this definition allows for modes that are not passive, provided that such modes are active infrequently enough.

First we summarize some related work on classical passivity and stability theory for nonlinear systems. The Willems-Hill-Moylan conditions provide necessary and sufficient conditions for continuous-time nonlinear systems to be passive [3], [5], [9]. Based on these conditions, the feedback passivity equivalence (i.e., conditions under which a nonpassive system can be rendered passive using feedback) for a continuous-time system is solved in [6]. The Willems-Hill-Moylan conditions specialize to the Kalman-Yacubovitch-Popov (KYP) conditions for continuous-time linear systems. In [7], [10], [11], the conditions have been extended to discrete-time nonlinear systems. The feedback losslessness equivalence and feedback passivity equivalence for discrete-time nonlinear systems has been proposed in [12] and [13], respectively.

There has also been considerable attention on the passivity/dissipativity of switched systems, however, most such works consider systems in which every mode is passive/dissipative. The works related to the present paper are in two primary categories. One line of work uses a common storage function for all modes to characterize the passivity/dissipativity of switched systems [14]–[17]. To get less conservative results, the use of multiple storage functions for different modes of a switched system has been proposed via piecewise quadratic storage functions [18], multiple storage functions and a common supply rate [19], and multiple storage functions and multiple supply rates [20]–[22]. For more general switched systems in which some modes can be nonpassive, only results that guarantee stability are available [23], [24]. Unlike these works, we are interested in system passivity in the presence of nonpassive modes.

The passivity definition that we develop can be considered to be analogous to the generalized asymptotic stability of
discrete-time nonlinear time-varying systems where the Lyapunov function is non-increasing not at every time step, but only on certain unbounded sets. However, unlike [25], the passivity analysis is complicated by the fact that passivity is an input-output property and both the inputs and the outputs of the system are time varying. Due to this difficulty, we analyze the feedback passivity properties of a switched system based on its zero dynamics ([1], [6], [26], and especially [13]). Zero dynamics are the internal dynamics of a system that are consistent with constraining the system output to zero. Under the proposed definition, we prove that a switched nonlinear system is locally feedback passive if and only if its zero dynamics are locally passive. A lower bound on the ratio of total activation time between feedback passive and non-feedback passive modes is then derived to guarantee passive zero dynamics.

The paper is organized as follows. Section II reviews the related background on classical passivity theory. In Section III, we introduce the switched nonlinear systems considered in this paper. In Section IV, we propose a generalized passivity definition and develop necessary and sufficient conditions for the passivity of the switched nonlinear systems. In Section V, we apply this definition to switched systems with passive, feedback passive, and non-feedback passive modes. The switched system is proved to be locally feedback passive if and only if its zero dynamics are passive. In Section VI, a lower bound on the total activation time of the (feedback) passive modes versus that of the non-feedback passive modes is derived to guarantee passive zero dynamics. In Section VII, we show that the classical properties of output feedback stabilizability and passivity preservation under parallel and feedback interconnections continue to hold under the new definitions. Two examples are provided in Section VIII. We conclude the paper in Section IX.

II. PRELIMINARY RESULTS

Table I summarizes the main notations used in this paper.

<table>
<thead>
<tr>
<th>Set</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathbb{R}_+$</td>
<td>set of positive real numbers</td>
</tr>
<tr>
<td>$\mathbb{Z}_+$</td>
<td>set of positive integers</td>
</tr>
<tr>
<td>$\mathbb{R}^n$</td>
<td>$n$-dimensional real vector</td>
</tr>
<tr>
<td>0</td>
<td>vector zero</td>
</tr>
<tr>
<td>0</td>
<td>scalar zero</td>
</tr>
<tr>
<td>$C^n$</td>
<td>$n$th order differentiable</td>
</tr>
</tbody>
</table>

TABLE I LIST OF NOTATIONS USED IN THE PAPER.

Consider a system of the form

\[
\begin{align*}
&x(k+1) = f(x(k), u(k)), \\
y(k) = h(x(k), u(k)),
\end{align*}
\]

where $x(k) \in \mathbb{X} \subset \mathbb{R}^n$, $u(k) \in \mathbb{U} \subset \mathbb{R}^m$, and $y(k) \in \mathbb{Y} \subset \mathbb{R}^m$ are the state, input, and output variables, respectively. $\mathbb{X}$, $\mathbb{U}$ and $\mathbb{Y}$ are the state, input, and output spaces, respectively. The time index $k \in \{0\} \cup \mathbb{Z}_+$ and $f$, $h$ are $C^\infty$ functions. All considerations are restricted to an open set $\mathbb{X} \times \mathbb{U}$ containing the equilibrium point $(x^*, u^*)$ with $x^* = f(x^*, u^*)$. For simplicity, assume that $(x^*, u^*) = (0, 0)$ and $h(0, 0) = 0$.

**Definition 2.1:** [12] A system of the form (1) is said to be **locally passive** with respect to the supply rate $u^T(k)y(k)$ if there exists a positive definite function $V(x)$, called the **storage function**, such that the following inequality holds

\[
V(f(x(k), u(k))) - V(x(k)) \leq u^T(k)y(k),
\]

$\forall x \in \mathbb{X}, u \in \mathbb{U}, k \in \{0\} \cup \mathbb{Z}_+$ (2)

with $\mathbb{X} \times \mathbb{U}$ being a neighborhood of the equilibrium point $(0, 0)$.

For our purpose, a condition equivalent to (2) will be more useful.

**Definition 2.2:** [13, Definition 3 and Theorem 5] A system of the form (1) is said to be locally passive with respect to the supply rate $u^T(k)y(k)$ if there exists a positive definite storage function $V(x)$ such that the following equation holds

\[
V(f(x(k), u(k))) - V(x(k)) = u^T(k)y(k) - (l(x(k)) + e(x(k))u(k))^T(l(x(k)) + e(x(k))u(k)) - m^T(x(k))m(x(k)), \quad \forall x \in \mathbb{X}, u \in \mathbb{U}, k,
\]

where $\mathbb{X} \times \mathbb{U}$ is a neighborhood of the equilibrium point $(0, 0)$ and $l(x(k)), e(x(k)), m(x(k))$ are real functions that are equal to zero if and only if $x(k) = 0$.

**Remark 2.1:** Definitions 2.1 and 2.2 are equivalent because the term $-(l + eu)^T(l + eu) - m^Tm$ is nonpositive. On the other hand, if there does not exist any storage function such that equation (3) holds, the system is nonpassive. Hence, we may associate a storage function with a nonpassive system and model its increase by the equation

\[
\begin{align*}
V(f(x(k), u(k))) - V(x(k)) &= u^T(k)y(k) + ((l(x(k)) + e(x(k))u(k))^T(l(x(k)) + e(x(k))u(k)) \\
&- m^T(x(k))m(x(k)), \quad \forall x \in \mathbb{X}, u \in \mathbb{U}, k,
\end{align*}
\]

(4)

where the term $(l + eu)^T(l + eu) - m^Tm$ can be either positive, negative, or zero.

Let $u(x(k), v(k))$ denote a nonlinear feedback control law. If $u(x(k), v(k))$ is locally regular, i.e., $\frac{\partial u(x(k), v(k))}{\partial v(k)} \neq 0$ for all $x(k), v(k)$, the system

\[
\begin{align*}
x(k+1) &= f(x(k), u(x(k), v(k))) \\
y(k) &= h(x(k), u(x(k), v(k))),
\end{align*}
\]

is referred to as the feedback transformed system of system (1). This transformed system can be used to study the passivity of system (1) via the following results.

**Proposition 2.1:** [26, Theorem 7.3] A system of the form (1) is said to be **locally feedback passive** if there exist a positive definite storage function $V(x)$ and a regular state feedback control law $u(x(k), v(k))$ with $v(k)$ as the new input such that $\forall x, v, k,$

\[
V(f(x(k), v(k))) - V(x(k)) \leq v^T(k)y(k).
\]

The zero dynamics ([11], [12]) of system (1) are given by constraining the system output to zero using control
supplied to it when a nonpassive mode is activated. In this paper, we generalize the classical passivity definition to such systems and investigate necessary and sufficiency conditions for passivity and feedback passivity.

Remark 3.1: The assumption of local relative degree zero and locally invertible \( J_{\sigma(k)} \) is reasonable because as shown in [12] and [26], respectively, a discrete-time nonlinear system can be rendered lossless/passive if and only if it has relative degree zero and lossless/passive zero dynamics. Therefore, in this paper, we will not study passivity of discrete-time systems with outputs that are independent of inputs. Note that recent work in [27] relaxes this assumption by using the coupled differential/difference representation (DDR) of the system. This, however, requires the existence of a control \( \mathbf{u} \) such that \( f(x,u) \) is invertible.

If we choose the feedback control law

\[
\mathbf{u}(k) = -J_{\sigma(k)}^{-1} h_{\sigma(k)} + J_{\sigma(k)}^{-1} \mathbf{v}(k)
\]

where \( \mathbf{v}(k) \) is an auxiliary input to be defined later, the transformed system dynamics become

\[
\begin{align*}
\mathbf{x}(k+1) &= f_{\sigma(k)}^*(\mathbf{x}(k)) + g_{\sigma(k)}^*(\mathbf{x}(k)) \mathbf{v}(k) \\
\mathbf{y}(k) &= \mathbf{v}(k),
\end{align*}
\]

where \( f_{\sigma(k)}^* \triangleq f_{\sigma(k)} - g_{\sigma(k)} \sigma^{-1}_{\sigma(k)} h_{\sigma(k)} \) and \( g_{\sigma(k)}^* \triangleq g_{\sigma(k)} \sigma^{-1}_{\sigma(k)} \). The zero dynamics of (9) are

\[
\begin{align*}
\mathbf{x}(k+1) &= f_{\sigma(k)}^*(\mathbf{x}(k)) \\
\mathbf{y}(k) &= \mathbf{0}.
\end{align*}
\]

Denote by \( \Sigma \) the switching sequence \( \{\sigma(0), \sigma(1), \cdots\} \). In this paper, we are interested in the following problems.

i. Since the dynamics of some of the modes are not passive, by classical definition (e.g., [17]), system (9) is not passive. However, if the non passive modes are active infrequently enough, the system must intuitively still be passive. In Section IV, we formalize this intuition by extending the traditional passivity definition. We also provide necessary and sufficient conditions for this definition to hold.

ii. In Sections V and VI, we use these conditions to prove that a nonpassive system can be rendered locally passive using feedback control laws if and only if its zero dynamics are locally passive.

iii. In Section VII, we prove that the proposed definition is consistent with the traditional definition of passivity in the sense that useful properties such as stability and compositionality are preserved.

IV. GENERALIZED PASSIVITY DEFINITION

In this section, we define a notion of passivity for system (9) that generalizes the existing definition of passivity for switched systems. We then derive necessary and sufficient conditions for the system to be passive under this definition.

Definition 4.1: The switched system (9) is said to be locally passive for a given switching sequence \( \Sigma \) if there exists a positive definite storage function \( V(x) : \mathbb{R}^n \rightarrow \mathbb{R}_+ \) such that for the state evolution under the switching sequence \( \Sigma \), the
following passivity inequality holds,
\[ V(x(T + 1)) - V(x(0)) \leq \sum_{k=0}^{T} u^T(k)y(k), \]
\[ \forall x \in X, u \in U, T \in \{0\} \cup \mathbb{Z}_{+}, \] (13)
with \( X \times U \) being a neighborhood of the equilibrium point \((0, 0)\).

**Remark 4.1:** There are two changes in this definition as compared to the classical definition given by the inequality (2). The first change is the consideration of the integral version of the change in storage function. This allows system (9) to have nonpassive modes as long as the increase in storage function over a finite horizon \( T \) is bounded by the total energy supplied to the system in the period \([0, T]\). The second change is to define the passivity for a particular switching sequence. Clearly, if a switched system is passive for any arbitrary switching sequence, every mode of the system must be passive. To allow for nonpassive modes, we must restrict the switching sequence. As we shall show in Section VI, Definition 4.1 allows us to prove the passivity of a switched system over wide sets of switching sequences.

We now extend the necessary and sufficient conditions for discrete-time nonlinear systems to be passive ([7], [10], [11]) to discrete-time switched nonlinear systems (9) under Definition 4.1. Before that, we summarize the assumptions for the storage function \( V \) which will be used in the following results.

**Assumption 6:** \( V \) is positive definite.

**Assumption 7:** \( V \) is \( C^2 \) and quadratic with respect to control.

**Theorem 4.1:** Suppose there exists a storage function \( V \), which is positive definite and \( C^2 \). Furthermore, let \( V(f_{\sigma(k)} + g_{\sigma(k)}u(k)) \) be quadratic in \( u \). Then the switched system (9) is passive for a given switching sequence \( \Sigma = \{\sigma(0), \sigma(1), \ldots\} \) with storage function \( V \) if and only if there exist real functions \( l_{\sigma(k)}(x(k)), m_{\sigma(k)}(x(k)), \) and \( e_{\sigma(k)}(x(k)) \) such that \( \forall T \in \{0\} \cup \mathbb{Z}_{+}, k = 0, 1, \ldots, T, \)

If \( \sigma(k) \in \mathcal{S}_1, \)
\[ V(f_{\sigma(k)} + g_{\sigma(k)}u(k)) - V(x(k)) = l_{\sigma(k)}^T f_{\sigma(k)} - m_{\sigma(k)}^T m_{\sigma(k)} \] (14a)
\[ \frac{\partial V(z)}{\partial z} \bigg|_{z = f_{\sigma(k)}} g_{\sigma(k)} = h_{\sigma(k)}^T (2l_{\sigma(k)} + e_{\sigma(k)}) e_{\sigma(k)} \] (14b)
\[ g_{\sigma(k)}^T \frac{\partial^2 V(z)}{\partial z^2} \bigg|_{z = f_{\sigma(k)}} g_{\sigma(k)} = J_{\sigma(k)}^T + J_{\sigma(k)} + 2e_{\sigma(k)}^T e_{\sigma(k)} \] (14c)

If \( \sigma(k) \in \mathcal{S}_2, \)
\[ V(f_{\sigma(k)} + g_{\sigma(k)}u(k)) - V(x(k)) = -l_{\sigma(k)}^T f_{\sigma(k)} - m_{\sigma(k)}^T m_{\sigma(k)} \] (15a)
\[ \frac{\partial V(z)}{\partial z} \bigg|_{z = f_{\sigma(k)}} g_{\sigma(k)} = h_{\sigma(k)}^T (2l_{\sigma(k)} + e_{\sigma(k)}) e_{\sigma(k)} \] (15b)
\[ g_{\sigma(k)}^T \frac{\partial^2 V(z)}{\partial z^2} \bigg|_{z = f_{\sigma(k)}} g_{\sigma(k)} = J_{\sigma(k)}^T + J_{\sigma(k)} + 2e_{\sigma(k)}^T e_{\sigma(k)} \] (15c)
\[ \sum_{k = 0}^{T} m_{\sigma(k)}^T m_{\sigma(k)} \leq \sum_{k = 0}^{T} m_{\sigma(k)}^T m_{\sigma(k)} \] (16)

**Proof.** The switched system (9) is composed of both passive and nonpassive modes. If the system is in a passive mode, i.e., \( \sigma(k) \in \mathcal{S}_2, \) according to equation (3), there exists a storage function such that \( \forall x \in X, u \in U, k, \)
\[ V(f_{\sigma(k)} + g_{\sigma(k)}u(k)) - V(x(k)) = u^T(k)y(k) - (l_{\sigma(k)} + e_{\sigma(k)}) u(k) \]
\[ - (l_{\sigma(k)} + e_{\sigma(k)}) u(k)) \]
\[ \leq \sum_{k = 0}^{T} m_{\sigma(k)}^T m_{\sigma(k)} \] (17)

If the system is in a nonpassive mode, i.e., \( \sigma(k) \in \mathcal{S}_1, \) according to equation (4), for any storage function \( V \) we have \( \forall x \in X, u \in U, k, \)
\[ V(f_{\sigma(k)} + g_{\sigma(k)}u(k)) - V(x(k)) = u^T(k)y(k) - (l_{\sigma(k)} + e_{\sigma(k)}) u(k) \]
\[ - (l_{\sigma(k)} + e_{\sigma(k)}) u(k)) \]
\[ \leq \sum_{k = 0}^{T} m_{\sigma(k)}^T m_{\sigma(k)} \] (18)

**(Necessity)** The proof has three parts.

i) We first show that equation (18) yields conditions (14a)- (14c) for nonpassive modes \( \sigma(k) \in \mathcal{S}_1, \) ii) Similarly, we show that equation (17) yields conditions (15a)- (15c) for passive modes \( \sigma(k) \in \mathcal{S}_2, \) iii) Based on the results from part i) and ii), we prove that the inequality (16) must hold if the switched system (9) is passive.

i) Because \( V(f_{\sigma(k)} + g_{\sigma(k)}u(k)) \) is quadratic in \( u, \) the Taylor series expansion of \( V(f_{\sigma(k)} + g_{\sigma(k)}u(k)) \) at the equilibrium \( u(k) = 0 \) is given by
\[ V(f_{\sigma(k)} + g_{\sigma(k)}u(k)) = V(f_{\sigma(k)}) + \frac{\partial V(z)}{\partial z} \bigg|_{z = f_{\sigma(k)}} g_{\sigma(k)} 
+ \frac{1}{2} \sum_{k = 0}^{T} m_{\sigma(k)}^T m_{\sigma(k)} \leq \sum_{k = 0}^{T} m_{\sigma(k)}^T m_{\sigma(k)} \] (19)
Therefore, it follows that
\[
V(f_{\sigma(k)} + g_{\sigma(k)}u(k)) - V(x(k)) = V(f_{\sigma(k)} - V(x(k)) + \frac{1}{2}u^T(k)g_{\sigma(k)}u(k) + \frac{1}{2}T_{\sigma(k)}L_{\sigma(k)}m_{\sigma(k)} - \sum_{k:s(\sigma(k)) \in S_2 \leq T} (l_{\sigma(k)} + e_{\sigma(k)}u(k))^T l_{\sigma(k)} + m_{\sigma(k)}(l_{\sigma(k)} + e_{\sigma(k)}u(k)) + m_{\sigma(k)}^T l_{\sigma(k)} + e_{\sigma(k)}u(k)) \right). (21)
\]

If inequality (16) holds, (21) implies that
\[
(25)
\]

**Definition 5.1:** The zero dynamics (12) of the switched system (9) are said to be locally passive for a given switching sequence \(\Sigma\) if there exists a positive definite storage function \(V(x) : \mathbb{R}^n \rightarrow \mathbb{R}_+\), such that for the state evolution under the switching sequence \(\Sigma\), the following passivity inequality holds,
\[
V(x(T+1)) - V(x(0)) \leq \sum_{k=0}^T w^T(k)y(k).
\]

**Lemma 5.1:** If the switched system (9) is locally feedback passive for a given switching sequence \(\Sigma\), then its zero dynamics (12) are also locally passive for the same switching sequence \(\Sigma\).

**Proof.** Because system (9) is locally feedback passive for the switching sequence \(\Sigma\), the inequality (25) holds. The zero dynamics enforces \(y(k) = 0\). Hence, the inequality (25) is converted to the inequality (22). That is, the zero dynamics (12) are also locally passive for the same switching sequence \(\Sigma\).  

Theorems 2.1 and 2.2 along with this result yields the following observation.

**Lemma 5.2:** The passive and feedback passive modes of the switched system (9) correspond to the passive modes of the zero dynamics (12). The non-feedback passive modes of the switched system (9) correspond to the nonpassive modes of
the zero dynamics (12).

Next, based on Theorem 4.1, we obtain the necessary and sufficient conditions for the switched system (9) to be feedback passive for a given switching sequence. We relate the passivity of system zero dynamics (12) to the feedback passivity of the switched nonlinear system (9) and provide a method to check the passivity of a given switched nonlinear system. This yields results analogous to those derived for discrete-time nonlinear (non-switched) systems in [12, Theorem 3.11], [13, Theorem 11], and in [26, Theorem 7.2].

Theorem 5.1: Suppose there exists a $C^2$ storage function $V$, which is positive definite and $V(f_{\sigma(k)} + g_{\sigma(k)}u(k))$ is quadratic in $u(k)$ for every possible value of $\sigma(k)$. Then, the switched nonlinear system (9) is locally feedback passive for a given switching sequence $\Sigma$ with the storage function $V$ if and only if its zero dynamics (12) are locally passive for the same switching sequence.

Proof. The necessity follows directly from Lemma 5.1. We next prove the sufficiency based on Theorem 4.1. More specifically, we prove that if the zero dynamics (12) are locally passive for a given switching sequence $\Sigma = \{\sigma(0), \sigma(1), \ldots\}$, conditions (14a)-(16) hold for the transformed system dynamics (24) with proper choices of the real functions $I_\sigma(k), e_\sigma(k)$ and $m_\sigma(k)$. Therefore, according to Theorem 4.1, the switched system (9) is locally feedback passive in the sense of Definition 5.2 for the switching sequence $\Sigma$.

We begin by relating the transformed system dynamics (24) with the zero dynamics (12) in terms of the storage function. Because $V(f_{\sigma(k)} + g_{\sigma(k)}u(k))$ is quadratic in $u$, the Taylor series expansion for $V(f_{\sigma(k)}^* + g_{\sigma(k)}^*\bar{h}_\sigma(k))$ can be expressed as follows:

$$V(f_{\sigma(k)}^* + g_{\sigma(k)}^*\bar{h}_\sigma(k)) = V(f_{\sigma(k)}^*) + \frac{\partial V}{\partial z}\bigg|_{z = f_{\sigma(k)}^*} g_{\sigma(k)}^*\bar{h}_\sigma(t) + \frac{1}{2}T_{\sigma(k)}(g_{\sigma(k)}^*)^T \frac{\partial^2 V}{\partial z^2}\bigg|_{z = f_{\sigma(k)}^*} g_{\sigma(k)}^*\bar{h}_\sigma(k).$$

Using equations (23) and (26), we have

$$V(f_{\sigma(k)}^* + g_{\sigma(k)}^*\bar{h}_\sigma(k)) = V(f_{\sigma(k)}^*) - \bar{h}_{\sigma(k)}^T \left(J_{\sigma(k)}^{-1}\bar{h}_{\sigma(k)} + \bar{h}_{\sigma(k)}(J_{\sigma(k)})^{-1}\bar{h}_{\sigma(k)} \right) = V(f_{\sigma(k)}^*).$$

We now consider two cases separately.

i) First consider the case when $\sigma(k) \in S_1 \cup S_2$. According to Lemma 5.2, in this case, the corresponding zero dynamics are passive. Based on equations (17) and (27), it follows that

$$V(f_{\sigma(k)}^*) - V(x(k)) = V(f_{\sigma(k)}^*) - V(x(k)) = -\left(I_\sigma(k) + e_\sigma(k)\bar{h}_\sigma(k)\right)^T \left(l_\sigma(k) + e_\sigma(k)\bar{h}_\sigma(k)\right) - m_\sigma(k) m_\sigma(k).$$

Equation (28) gives the passivity condition (15a) with $I_\sigma(k) = l_\sigma(k) + e_\sigma(k)\bar{h}_\sigma(k)$ and $m_\sigma(k) = m_\sigma(k)$ for the transformed system dynamics (24).

Next, subtract $V$ from equation (26) and substitute equation (28) into the resulting equation to obtain

$$V(f_{\sigma(k)}^* + g_{\sigma(k)}^*\bar{h}_\sigma(k)) = V(x(k)) = -\left(l_\sigma(k) + e_\sigma(k)\bar{h}_\sigma(k)\right)^T \left(l_\sigma(k) + e_\sigma(k)\bar{h}_\sigma(k)\right) - m_\sigma(k) m_\sigma(k).$$

$$-\frac{1}{2}T_{\sigma(k)}(g_{\sigma(k)}^*)^T \frac{\partial^2 V}{\partial z^2}\bigg|_{z = f_{\sigma(k)}^*} g_{\sigma(k)}^*\bar{h}_\sigma(k) = \frac{1}{2}T_{\sigma(k)}(g_{\sigma(k)}^*)^T \frac{\partial^2 V}{\partial z^2}\bigg|_{z = f_{\sigma(k)}^*} g_{\sigma(k)}^*\bar{h}_\sigma(k).$$

Differentiating both sides of equation (29) with respect to $\bar{h}_\sigma(k)$, right multiplying the result by $J_{\sigma(k)}^T$, and substituting equation (23), we obtain

$$\frac{\partial V}{\partial z}\bigg|_{z = f_{\sigma(k)}^* + g_{\sigma(k)}^*\bar{h}_\sigma(k)} g_{\sigma(k)}^*f_{\sigma(k)}^T = \bar{h}_\sigma^T - 2\left(l_\sigma(k) + e_\sigma(k)\bar{h}_\sigma(k)\right)^T e_\sigma(k)J_{\sigma(k)}^T.$$

Therefore, equation (30) yields the passivity condition (15b) with $l_\sigma(k) = l_\sigma(k) + e_\sigma(k)\bar{h}_\sigma(k)$ and $m_\sigma(k) = m_\sigma(k)J_{\sigma(k)}$ for the transformed system dynamics (24).

Now take the second-order derivatives of equation (29) with respect to $\bar{h}_\sigma(k)$. Right multiply the results by $J_{\sigma(k)}^T$ and right multiply by $J_{\sigma(k)}$, and use equation (23) to obtain

$$\left[g_{\sigma(k)}^*J_{\sigma(k)}^T\right]^T \frac{\partial^2 V}{\partial z^2}\bigg|_{z = f_{\sigma(k)}^* + g_{\sigma(k)}^*\bar{h}_\sigma(k)} g_{\sigma(k)}^*f_{\sigma(k)}^T = J_{\sigma(k)}^T + J_{\sigma(k)}^2 + 2J_{\sigma(k)}^T e_{\sigma(k)}^T J_{\sigma(k)}.$$
With $e_{\sigma(k)} = 0$, the condition (16) reduces to
\[
\sum_{k: \sigma(k) \in S_1 \setminus S_1^*} \mathcal{I}_{\sigma(k)} T^\sigma_{0} \leq \sum_{k: \sigma(k) \in S_2 \cup S_1^*} \mathcal{I}_{\sigma(k)} T^\sigma_{0},
\]
(33)

Because the zero dynamics of the switched system are passive under the passivity definition 4.1 for the switching sequence $\Sigma$, the above inequality naturally holds. Hence, all the conditions in Theorem 4.1 are satisfied and the switched system (9) is locally feedback passive for the switching sequence $\Sigma$. \hfill \blacksquare

VI. SWITCHING SEQUENCE FOR PASSIVE ZERO DYNAMICS

We now formalize the intuition that a switched system is passive for a given switching sequence if the nonpassive modes are active infrequently enough. To this end, we derive a lower bound on the ratio of the total activation time of (feedback) passive versus nonpassive modes such that the system zero dynamics (12) are passive.

According to Lemma 5.2, the passive and feedback passive modes of the switched system (9) correspond to the passive modes of the zero dynamics. When $\sigma \in S_2 \cup S_1^*$, we assume that the storage function $V$ evolve such that
\[
V(f^\sigma_*(x)) \leq L_\sigma V(x),
\]
\[
0 < L_\sigma < 1, \quad \sigma \in S_2 \cup S_1^*, \quad \forall x.
\]
(34)

Let $L_1 = \max \{L_\sigma | \sigma \in S_2 \cup S_1^*\}$ be the maximum bound among all passive modes. Admittedly, $L_\sigma < 1$ being constant for all $x \in X$ may be a strong assumption.

Similarly, according to Lemma 5.2, the non-feedback passive modes of the switched system correspond to the nonpassive modes of the zero dynamics. Therefore, when $\sigma \in S_1 \setminus S_1^*$, the storage function $V$ evolves in a way such that
\[
V(f^\sigma_*(x)) \leq L_\sigma V(x),
\]
\[
L_\sigma > 1, \quad \sigma \in S_1 \setminus S_1^*, \quad \forall x.
\]
(35)

Let $L_2 = \max \{L_\sigma | \sigma \in S_1 \setminus S_1^*\}$ be the maximum bound among all nonpassive modes.

**Theorem 6.1:** Consider the zero dynamics (12) with multiple passive and nonpassive modes. Assume that conditions (34) and (35) hold when the zero dynamics evolve in passive and nonpassive modes, respectively. Design the switching sequence such that
\[
\frac{K^-(0, T)}{K^+(0, T)} \geq \frac{\ln L_2 - \ln L_0}{\ln L_0 - \ln L_1},
\]
(36)

where $L_0 \in (L_1, 1)$, $K^-(0, T)$ is the total activation time of the passive and feedback passive modes, and $K^+(0, T)$ is the total activation time of the non-feedback passive modes during time interval $[0, T]$, $\forall T \in \{0\} \cup \mathbb{Z}_+$. The zero dynamics (12) are passive under the switching sequence governed by (36).

**Proof.** Let $0 = k_0 < k_1 < k_2 \cdots$ denote the switching points and $\sigma(k_{i-1}) = p_i$. Assume that $k_i$ is the time step corresponding to the $i$th switch, the storage function of the zero dynamics evolves as
\[
V(x(k_i)) \leq L_{p_i}^{k_i-k_{i-1}} V(x(k_{i-1}))
\]
\[
\leq \begin{cases} 
L_{k_i-k_{i-1}} V(x(k_{i-1})), & p_i \in S_2 \cup S_1^* \\
L_{k_i-k_{i-1}}^{k_i-k_{i-1}} V(x(k_{i-1})), & p_i \in S_1 \setminus S_1^*.
\end{cases}
\]

At time $T \in [k_i, k_{i+1})$, we obtain
\[
V(x(T)) \leq L_T^{k_i-k_{i-1}} V(x(k_{i-1})) \leq \cdots \leq L_T^{k_i-k_{i-1}} \cdots L_{k_i-k_0} V(x(0)).
\]

Based on conditions (34) and (35), at time $T$, we have
\[
V(x(T)) \leq L_1^{K^-(0, T)} L_2^{K^+(0, T)} V(x(0)).
\]

From the switching sequence governed by (36), we have
\[
\ln \left( \frac{\ln L_2}{\ln L_0} K^-(0, T) \right) \geq \ln \left( \frac{\ln L_2}{\ln L_0} K^+(0, T) \right),
\]
or
\[
\frac{L_0}{L_1} K^-(0, T) \geq \left( \frac{L_0}{L_1} \right) K^+(0, T),
\]
or
\[
L_0^{K^-(0, T)} K^+(0, T) \geq L_1^{K^-(0, T)} L_2^{K^+(0, T)}.
\]

Because $K^-(0, T) + K^+(0, T) = T$, it follows that
\[
V(x(T)) \leq L_1^{K^-(0, T)} L_2^{K^+(0, T)} V(x(0)) \leq L_0^T V(x(0)).
\]
(37)

Because $L_0 \in (L_1, 1)$, we have $V(x(T)) \leq V(x(0))$, or equivalently, the zero dynamics (12) are passive.

**Remark 6.1:** The switching law (36) indicates that the closer $L_0$ to 1 the less conservative the bound is.

VII. STABILITY & COMPOSITIONALITY PROPERTIES

In this section, we prove that feedback passivity definition 5.2 preserves two useful properties of the classical passivity definition. Specifically, we show that a feedback passive switched system of the form (9) can achieve asymptotic stability using output feedback if the system is zero state detectable, and that the parallel and negative feedback interconnections of two such feedback passive switched systems remain feedback passive.

**Definition 7.1:** A system is said to be locally zero state detectable (ZSD) [7] if there exists a neighbourhood $N$ of the origin such that $\forall x(0) = x_0 \in N$,
\[
y(k)|_{u(k) = 0} = h(\psi(k; x_0)) = 0, \quad \forall k \in \mathbb{Z}_+.
\]

implies
\[
\lim_{k \to +\infty} \psi(k; x_0) = 0,
\]
where $\psi(k; x_0)$ is a trajectory of the uncontrolled system $x(k + 1) = f(x(k))$ from $x(0) = x_0$.

**Theorem 7.1:** If the zero dynamics (12) of system (9) satisfy conditions (34) and (35), then system (9) is locally feedback passive for any switching sequence governed by (36) with a $C^2$ storage function. Let $\phi: \mathbb{R}^m \to \mathbb{R}^m$ be any smooth function such that $\phi(0) = 0$ and $\mathcal{V}^\phi(y) > 0$ for all $y \neq 0$. Then
the smooth feedback control law \( w(k) = -\phi(y(k)) \) locally asymptotically stabilizes the equilibrium \( x^* = 0 \), provided that \( 9 \) is locally ZSD.

**Proof.** According to Theorem 6.1, under the switching sequence governed by (36), system zero dynamics (12) satisfying the condition (34) and (35) are feedback passive. From Theorem 5.1, the switched system (9) is locally feedback passive given the passive zero dynamics (12) for a given switching sequence governed by (36).

When \( \sigma(k) \in S_2 \cup S_1^r \), we have
\[
V(x(k+1)) - V(x(k)) \leq w^T(k)y(k).
\]
Therefore, any trajectory of the (feedback) passive system satisfies
\[
V(x(k+1)) - V(x(k)) \leq -y^T\phi(y(k)) \leq 0.
\]
Under the switching sequence governed by (36), when \( \sigma(k) \in S_1 \setminus S_1^r \), the storage function may increase. However, the increase is always bounded since \( V(x(k)) \leq L_0^k V(x(0)) \), \( L_0 \in (L_1, 1) \). Now define the sequence of time steps \( \{t_i\} \) such that \( t_0 = 0 \) and \( t_i \) is the least time \( > t_{i-1} \) such that \( \sigma(t_i) \in S_1 \cup S_1^r \) and \( \sigma(t_i) \in S_1 \cup S_1^r \). Then, by an argument identical to above, we can derive a series of inequalities
\[
V(x(t_{i+1})) - V(x(t_i)) \leq 0,
\]
where \( \forall i = 0, 1, \ldots, \forall x \in X \). (38)

Since the frequency in which \( \sigma(t_i) \in S_2 \cup S_1^r \) is infinitely often, \( \{t_i\} \) is an infinite sequence. Then \( V \) is a Lyapunov function for the system \( S \) by which Theorem 2 in [25] implies that the system is Lyapunov stable. The asymptotic stability now follows from ZSD. \( \square \)

Next, we show the preservation of generalized passivity for interconnected systems.

**Theorem 7.2:** If two switched nonlinear systems of the form (9) are both feedback passive, then their parallel and negative feedback interconnections (as defined in Figure 1) are both feedback passive.

**Proof.** Let the control inputs for \( S_1 \) be \( w_1(k) \), the corresponding output be \( y_1(k) \) and the storage function be \( V_1(k) \). For the parallel interconnection, we have for the interconnected system \( S_p \), the control input \( r(k) = w_1(k) = w_2(k) \) and the output \( y(k) = y_1(k) + y_2(k) \). Consider the storage function \( V(k) = V_1(k) + V_2(k) \). For any time \( T \in (0) \cup \mathbb{Z}^+ \), we have
\[
V(x(T+1)) - V(x(0)) \leq \sum_{k=0}^{T} r^T(k)y(k).
\]
Similarly, for the negative feedback interconnection, we have for the interconnected system \( S_f \), the control inputs and outputs as \( r_1(k) = w_1(k) + y_2(k) \) and \( r_2(k) = w_2(k) - y_1(k) \). Consider the storage function \( V(k) = V_1(k) + V_2(k) \). For any time \( T \in (0) \cup \mathbb{Z}^+ \), we have
\[
V(x(T+1)) - V(x(0)) \leq \sum_{k=0}^{T} (r^T_1(k)y_1(k) + r^T_2(k)y_2(k)).
\]

**VIII. Examples**

In this section, we provide two examples to present the feedback passivity results proposed in Sections V and VI. We first give an example of a thermal system with linear switched dynamics and then discuss a more general numerical example of nonlinear switched system.

**A. Quenching with Variable Bath Properties**

Quenching is a process in which a heated object is placed into a liquid bath. The process can improve hardness and other properties of metal by rapid cooling. Consider a metal cube immersed in liquid bath, the model of the cube temperature \( T_1(t) \) and liquid bath temperature \( T_2(t) \) can be represented by the following linear differential equation:
\[
C_1 \frac{dT_1(t)}{dt} = -\frac{1}{R_1} (T_1(t) - T_2(t))
\]
\[
C_2 \frac{dT_2(t)}{dt} = \frac{1}{R_1} (T_1(t) - T_2(t)) - \frac{1}{R_2} (T_2(t) - T_o(t)),
\]
where \( C_1, C_2 \) are the capacitances of the cube and the liquid bath, respectively, \( R_1 \) is the convective resistance between the cube and the bath, \( R_2 \) is the combined convective/conductive resistance of the container wall and the liquid surface, and \( T_o \) is the temperature outside the bath. Using Euler approximation to discretize the system, we have
\[
T_1(k+1) = (1 - \frac{T_s}{R_1C_1})T_1(k) + \frac{T_s}{R_1C_1} T_2(k)
\]
\[
T_2(k+1) = \frac{T_s}{R_1C_2} T_1(k) + (1 - \frac{T_s}{R_1C_2} - \frac{T_s}{R_2C_2}) T_2(k) + u(k),
\]
where \( T_s \) is the sampling time and the control input is set as \( u(k) = \frac{T_s}{R_2C_2} T_o(k) \). Let the output be
\[
y(k) = \frac{T_s}{C_3R_3} (T_1(k) - T_2(k)) + u(k).
\]

In the simulation, we set the capacitance and resistance of the metal cube as \( C_1 = 100 \), \( R_1 = 0.018 \). Now we vary the bath properties \( C_2, R_2 \) so that 3 modes representing different bath properties can be simulated. We have Mode

![Fig. 1](image-url)

Fig. 1. (a) Parallel, and (b) negative feedback interconnections for two feedback passive switched nonlinear systems \( S_1 \) and \( S_2 \).
1 (nonpassive), Mode 2 (passive), and Mode 3 (feedback passive). Table II lists the bath properties $C_2, R_2$, output parameters $C_3, R_3$, and $L_\sigma$ in conditions (34) and (35) for the 3 modes.

The sampling time is set as $T_s = 1$ and we choose the Lyapunov function as $V = \frac{1}{2}(T_2^2(k) + T_3^2(k))$ which is $C^2$ and $V(f_{\sigma(k)} + g_\sigma(k)\mathbf{u})$ quadratic in $\mathbf{u}$. The storage function is chosen as $V = \frac{1}{2}(x_1^2(k) + x_2^2(k))$ which satisfies A.6 and A.7. The resulting switching law is

$$K^-(0, T) \geq 0.5557K^+(0, T).$$

More insight can be obtained if we consider the system operating over a finite horizon. Consider the system operation from $k = 1$ to $T = 16$. Figure 2(a) shows the system passivity check under the classical definition, i.e., inequality (2). We see from the figure that the inequality does not always hold when the system is in the non-feedback passive Mode 1, i.e., at time steps 2, 6, 9, 13. Hence, the switched system is considered to be nonpassive in the classical passivity theory. Figure 2(b) shows the passivity check under the generalized definition, i.e., inequality (25) which is satisfied at every time step.

### B. Numerical Nonlinear Example

Consider a switched nonlinear system consisted of the following three modes

(Mode 1)

$$x_1(k+1) = (2x_2(k) + 0.8x_1^2(k) + u(k)) \cos(x_2(k))$$

$$x_2(k+1) = (1.6x_1(k) + 0.2x_2^2(k) + u(k)) \sin(x_2(k))$$

$$y(k) = x_1(k) + x_2(k) + u(k).$$

Mode 1 is nonpassive and can not be passivated using feedback and $L_\sigma = 1.5506$.

(Mode 2)

$$x_1(k+1) = x_2^2(k) + u(k)$$

$$x_2(k+1) = 0.6x_1^2(k) + u(k)$$

$$y(k) = 0.8x_1^2(k) + 0.75x_2^2(k) + u(k).$$

Mode 2 is locally passive and $L_\sigma = 0.2666$.

(Mode 3)

$$x_1(k+1) = x_1^2(k) + x_2^2(k) + u(k)$$

$$x_2(k+1) = x_1^2(k) - 0.3x_2^2(k) + u(k)$$

$$y(k) = x_1^2(k) + x_2^2(k) + u(k).$$

Mode 3 is a locally feedback passive mode and $L_\sigma = 0.3702$. Therefore, we have $L_1 = 0.3702$ and $L_2 = 1.5506$ and we choose $L_0 = 0.9999$. The resulting switching law is

$$K^-(0, T) \geq 0.4416K^+(0, T).$$

Modes 2 and 3 are ZSD. The design of feedback control is as follows. We take Mode 3 as an example, and the derivation of the other two modes follows similarly as in Section V.

$$J_3(k) = 2$$

$$h_3(k) = -2 \left(2x_1^2(k) + 0.7x_2^2(k)ight)$$

$$-2(x_1^2(k) + x_2^2(k))$$

$$w(k) = -200y(k)$$

The storage function is chosen as $V = \frac{1}{2}(x_1^2(k) + x_2^2(k))$.

Under the switching law (40), the zero dynamics of the switched system satisfy the generalized passivity inequality as shown in Figure 3(a)(i). Figure 3(a)(ii) shows that the evolution of storage function for zero dynamics satisfy the inequality (37). Figure 3(b) shows the evolution of state dynamics and both states converge to the equilibrium point. Figure 4(a) shows the system passivity check under the classical definition, i.e., inequality (2). Figure 4(b) shows the passivity check under the generalized definition, i.e., inequality (25) which is always satisfied. Table III lists the activation time of each mode during the horizon. The switching condition (40) can be verified at every time step till $T$. 

### TABLE II

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_2$</td>
<td>50</td>
<td>100</td>
<td>55</td>
</tr>
<tr>
<td>$R_2$</td>
<td>0.2</td>
<td>0.019</td>
<td>0.03</td>
</tr>
<tr>
<td>$C_3$</td>
<td>900</td>
<td>900</td>
<td>122.22</td>
</tr>
<tr>
<td>$R_3$</td>
<td>0.0165</td>
<td>0.0092</td>
<td>0.0112</td>
</tr>
<tr>
<td>$L_\sigma$</td>
<td>1.2812</td>
<td>0.6029</td>
<td>0.5089</td>
</tr>
</tbody>
</table>
generalized passive systems remain passive. Stability using output feedback and the interconnections of two time of (feedback) passive modes versus non-feedback passivity definition. A lower bound on the total activation zero dynamics are locally passive according to the generalized definition. We prove that the system equilibrium point can achieve asymptotic stability using output feedback and the interconnections of two generalized passive systems remain passive.

IX. CONCLUSION
In this paper, we generalize the classical passivity definition for a class of discrete-time switched nonlinear systems consisting of both passive and nonpassive modes. We introduce necessary and sufficient conditions for such systems to be locally passive according to the generalized definition. We further apply these results to switched systems with passive modes, feedback passive modes, and modes that cannot be rendered passive using feedback. The switched nonlinear system is proved to be locally feedback passive if and only if its zero dynamics are locally passive according to the generalized passivity definition. A lower bound on the total activation time of (feedback) passive modes versus non-feedback passive modes is derived to guarantee passive zero dynamics. We prove that the system equilibrium point can achieve asymptotic stability using output feedback and the interconnections of two generalized passive systems remain passive.

REFERENCES

Fig. 3. (a) (i) Passivity check for system zero dynamics according to inequality (22), (a) (ii) Check for inequality (37), and (b) Evolution of state dynamics using control law $w(k)$

![Zero Dynamics](image1)

![Storage Function Evolution](image2)

![Mode Activation](image3)

Table III

<table>
<thead>
<tr>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Fig. 4. (a) Passivity check for the switched system according to the classical passivity definition (2) using control law $u(k)$, and (b) Feedback passivity check for the switched system according to the generalized passivity definition (25) using control law $\tilde{w}(k)$.

![Passivity Check](image4)

![Feedback Check](image5)

![Activation Time](image6)

TABLE III

<table>
<thead>
<tr>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>


Vijay Gupta is an Associate Professor in the Department of Electrical Engineering at the University of Notre Dame. He received his B. Tech degree from the Indian Institute of Technology, Delhi and the M.S. and Ph.D. degrees from the California Institute of Technology, all in Electrical Engineering. He has served as a research associate in the Institute for Systems Research at the University of Maryland, College Park, and as a consultant to the Systems Group at the United Technology Research Center, Hartford, CT. His research interests include various topics at the interaction of communication, computation and control. He has served as a research associate in the Institute for Systems Research at the University of Maryland, College Park, and as a consultant to the Systems Group at the United Technology Research Center, Hartford, CT. His research interests include various topics at the interaction of communication, computation and control. He received the NSF Career award in 2009 and the Donald P. Eckman award in 2013.

Panos J. Antsaklis is the Brosey Professor of Electrical Engineering at the University of Notre Dame. He is a graduate of the National Technical University of Athens, Greece, and holds MS and PhD degrees from Brown University. His research addresses problems of control and automation and examines ways to design control systems that will exhibit high degree of autonomy. His recent research focuses on Cyber-Physical Systems and addresses problems in the interdisciplinary research area of control, computing and communication networks, and on hybrid and discrete event dynamical systems. He has co-authored two research monographs on discrete event systems, two graduate textbooks on Linear Systems and has co-edited six books on Intelligent Autonomous Control, Hybrid Systems and Networked Embedded Control Systems. He is IEEE, IFAC and AAS Fellow, the 2006 recipient of the Engineering Alumni Medal of Brown University and a 2012 honorary doctorate recipient from the University of Lorraine, France. He is the Editor-in-Chief of the IEEE Transactions on Automatic Control.

Yue Wang is an Assistant Professor in the Department of Mechanical Engineering at Clemson University. She received her B. S. degree from Shanghai University, China, and M.S. and Ph.D. degrees from Worcester Polytechnic Institute. Prior to joining Clemson, she was a postdoctoral research associate in the Electrical Engineering Department at the University of Notre Dame. Her research interests include compositional design and control of cyber-physical systems, decision-making for multi-agent systems, and collaborative human robot teams.