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Navigating Stability in Designing Cyber-Physical Systems with Dissipative Strategies

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Abstract:

Large numbers of diverse cyber and physical subsystems that are networked, tightly interact, and have the ability to grow or shrink are all features of cyber-physical systems. It is extremely difficult to design and maintain a CPS's attributes over time. Concepts like passivity and dissipative, which resemble energy, have significant potential for ensuring attributes like stability in intricate, diverse, interconnected systems that are undergoing dynamic change. Results for continuous, discrete, and switched systems in networks with delays, event-triggered architectures, conic systems, and systems with symmetries are shown. Passivity indices, which provide a measure of the degree of passivity, are used to generalize classical results in interconnected systems

Keywords: *CPS, Dissipativity, Passive Switch Systems, quantum physics and crystallography*

Introduction:

Recent advancements in computing, sensing, communications, control, and other fields have given resurgence to a new class of complex systems known as cyber-physical systems (CPS). The characteristics of Cyber-Physical Systems include large a network's tightly connected, continuously expanding and contracting heterogeneous components. Cyber-physical systems are widely used and getting more so every day. Smart grids, smart buildings, smart energy systems, smart transportation systems, and smart medical devices are a few examples of CPS in action. Such systems are extremely difficult to control and call for designs that combine elements of discrete event systems, hybrid control systems, classical control, and networked control. Furthermore, when redesigning dynamic systems, robustness, reliability, and security concerns need to be taken into consideration. This blending of several scientific fields and technologies. Over the past seven years, a number of research projects in CPS have been conducted and details are available in CPS virtual organization website. Although CPS is made up of networked heterogeneous subsystems, the number of these subsystems varies, one must ensure certain properties of the entire system during the design process. Our study on the passivity and dissipativity-based CPS design is summarized in the sections that follow. Networking passively switched systems is specifically addressed in Section [2]. This assumes switched systems are connected over a network with potential delays, lost data, and quantization and applies a well accepted definition of passivity for switched systems. In Section [3], the use of event-triggered control in passive systems is discussed. Reducing network communication to ensure a certain performance level has been accomplished through the use of event-triggered control. In Section [4] applies passivity to multi-agent systems whose connections display some type of symmetry. Lastly, In Section [5] we conclude with final thoughts.

Passive Switched Systems Networking:

In CPS, differential or difference equations with a significant time dependence are used to simulate physical processes. The cyber processes are modelled based on change in response to events that transpire in software and in the physical world. They are modelled by employing discrete-event models, like Petri nets or finite automata. When these various parts are combined, system models that are switched or hybrid are produced. The fact that these intricate systems are frequently composed of disparate parts presents which is one of the exigent parts CPS. Analyzing these systems' stability requires an understanding of their compositionality attribute. Dissipativity or passivity theory is one method of approaching compositionality. When two systems are coupled in parallel or with negative feedback,

The dynamical trait known as passivity. Passivity suggests stability under modest assumptions. By gradually joining passive components together, large-scale stable systems can be constructed using these two qualities. Within the context of switched systems, dissipativity qualities can also be investigated. Dissipativity is a quality that is kept in feedback, even though dissipative systems might not be stable. Stability can be determined from the dissipative rate of interconnection. A generalized passivity feature for switched systems may be used in CPS to take advantage of the compositionality that passivity offers. It is possible to utilize a general model of nonlinear switching systems. In order to prevent the Zeno phenomenon, switching between subsystems is supposed to be constrained on any finite time interval. Generally it is observed if the underline following criteria are met, then a switched system is considered as passive. (i) When the subsystem is functioning it is considered to be passive state.(ii)In an inactive state every subsystem dissipates. The second requirement restricts the general form of dissipativity because it requires the existence of inputs to guarantee that switching contributes a finite quantity of energy over an infinite time horizon. The anticipated characteristics of passive systems are expanded upon by this definition. First, when passive switched systems are connected in negative feedback, passivity is maintained. Second, expected stability results are displayed when the definitions are somewhat tightened. This comprises output that is strictly passive and implies L2 stability (bounded input, bounded output stability), as well as strictly passive indicating asymptotic stability.

While many useful systems are passive, however there are switched system which aren't always passive that are used in some applications. One method is to apply the feedback stability result to these non passive systems in the passivity index domain. This framework, which measures the degree of passivity in a particular system, generalizes the feature. Two indices are necessary to fully characterize the level in a system. The system's degree of stability is gauged by the first. The second quantifies the system's minimal phase property's extent. Conic System theory closely related to this approach. Applying the indices to switched systems differs primarily to that indices which are now fluctuate over time. The two indices are assigned values to each subsystem, and during the periods when that subsystem is operating, the values of the indices are transferred to the overall switching system. According to this definition, switched systems' passivity indices are piecewise constant. The switching signals behave properly and the time-varying indices are well-defined under the previous premise that there is finite switching on any finite time period. The outcomes derived from the indices apply to switched systems in a broad way. From a conceptual standpoint, if two systems are connected by feedback, then a deficiency in passivity in one system can be offset by an excess of passivity in the other. As stated in reference [6], an excess of the minimum phase feature in one system might make up for a deficiency in stability in another system. It is feasible for determining whether the matrix is positive definite in order to verify the interconnection of the wo switched system is stable once the indices have been evaluated. This implies that even in cases when the systems within the loop are neither passive or stable, stable feedback loops can still be can be created. Being connected by numerous components over communication routes that experience packet loss and delayed data presents another difficulty for CPS. While two switched systems connected in feedback maintain passivity, the introduction of delays breaks this state. Passivity demands instantaneous energy transmission from one side of the network to the other since it is an energy-based attribute with a substantial temporal dependence. Decoupling the concept of energy defined by passivity over a network interface is one way to address this problem. The interface transforms input-output coordinates to wave variables in an invertible manner. Although the wave variable transformation is well-established for non-switched systems, switched models are necessary for many CPS domains. This method can handle lost data from packet dropouts and time-varying delays with an upper bound.

Additional problems with networking CPS include quantization and discretization. These are frequent problems that arise when signals are quantized for usage in digital networks or when continuous-time physical processes are sampled for control by digital controllers. The discretization of passive systems has been extensively researched, while quantization has are less explored. The primary issue is that when quantization occurs, the stability conclusions drawn from passivity theory are no longer valid .In the research article[8] it is presented a control paradigm that allows input and output quantization while maintaining passivity for both switched and non-switched systems provided that the quantizers have finite gains,and they can be universal and have non-uniform levels.

Passive System Controlled by Event:

It has been proposed recently by a number of academics that event-based control is a potentially useful method for controlling numerous control applications by lowering computing and communication load. An "event triggering condition" violation on specific signals, which causes the control actions to be recalculated, is the standard event-based implementation's method of maintaining constant control signals. The potential to decrease computations and transmissions while maintaining desired performance levels makes event-based control highly desirable in networked control systems (NCSs) when compared to time-driven control, which applies a constant sampling period to ensure stability in the worst-case scenario. For stochastic systems, a comparison between time-driven and event-driven control is presented in [9], favouring the latter. A deterministic event-triggered control strategy is presented in [11], [12], and output-based event-triggering control with guaranteed $L\infty$-gain for linear time-invariant systems has been explored in [15]. Event-triggering stabilization for distributed networked control systems has been examined in [13], and a self-triggered coordination strategy for the best possible deployment of mobile robotics is suggested in [14]. For stochastic systems, a comparison between time-driven and event-driven control is presented in [9], favouring the latter. A deterministic event-triggered control strategy is presented in [11], [12], and output-based event-triggering control with guaranteed $L\infty$-gain for linear time-invariant systems has been explored in [15]. Event-triggering stabilization for distributed networked control systems has been examined in [13], and a self-triggered coordination strategy for the best possible deployment of mobile robotics is suggested in [14]. Studying the stability and effectiveness of event-triggered control systems with dynamic and static output feedback controllers is crucial since, in many control applications, the complete state information is not available for assessment.

A static output feedback-based event-triggered control method for output feedback passive (OFP) and passive NCS stabilization is presented in [16]. Based on the plant's output feedback passivity indices, a static output feedback gain and a triggering condition are determined. An event-triggered control strategy based on dynamic output feedback is presented in [17] to stabilize input feed-forward output feedback passive (IF-OFP) NCSs. This work builds upon our earlier work in [16] to stabilize more general dissipative systems.

The passivity theorem serves as the foundation for the triggering condition, which enables us to characterize a broad class of output feedback stabilization controllers. We demonstrate that the control system is finite gain L2 stable in the presence of bounded external disturbances under the triggering condition derived in [17]. In terms of the passivity indices of the controller and the plant, the relationships among the triggering condition, the feasible L2 gain of the control system, and the inter-sampling time have been examined. Our proposal for an event-triggered control setup for NCSs is based on the findings in [17]. This setup enables us to account for network-induced delays in two directions: from the controller to the plant and from the sampler to the controller [18]. It is demonstrated by us that the suggested configuration allows for the attainment of finite-gain L2 stability even while dealing with random, constant network-induced delays or delays that have limited noise.

With the potential to lower implementation costs and communication load, event-based distributed control is a promising approach for cooperative control of multi-agent systems. For the stabilization of large-scale networked control systems with finite-gain L2 stability, we suggest a distributed event-driven communication technique in [19]. A subsystem's local output inaccuracy surpasses a certain threshold, at which point it broadcasts its output information to neighbouring subsystems. It is related to the underlying communication graph topology that the triggering circumstance is present. In addition, we offer an examination of the intervals of time (referred to as the inter-event time) that separate two successive transmissions. It is evident from our investigation that the NCSs s performance with event-driven communication is significantly influenced by the topology of the communication graph underneath

Symmetry and Passivity:

As a fundamental property of shapes and graphs, symmetry arises from the process of tree-like or cyclic development and can be found in many real-world networks, including the Internet and power grid. The study of symmetry has proven interesting in many scientific fields, including Lie groups in quantum physics and crystallography in chemistry, since it is associated with the idea of a high degree of repetitions or regularities. Symmetry has been thoroughly examined in the classical theory of dynamical systems. Under certain circumstances, multi-agent systems with different information constraints and protocols can be expressed as or broken down into inter connections of lower dimensional systems which may improve comprehension of properties like controllability and stability. The dynamics of the system are therefore invariant by coordinate transformations because of the presence of symmetry in this situation. In our study, agents are categorized into symmetry groups and local control laws are applied under limited interconnections with neighbours to derive stability conditions for large-scale systems.

An extension of passivity is dissipative, which allows for a system to receive energy in various forms. Multiple dynamical system attributes is obtained through altering the pace of energy supply. Studying overall stability qualities is possible when a symmetric system's subsystems are dissipative. Large-scale systems with symmetric interconnections can be synthesized using these results, which provide conditions for the greatest number of subsystems that can be added without compromising stability.

Let's examine the interrelated nonlinear distributed dynamics Σ_0, Σ_1 ……..Σ_n be given by

$$\Sigma_i: \begin{array}{l} \dot{a}_i = f(a_i) + p_i(a_i)k_i \\ b_i = d_i(a_i) \\ k_i = k_{gi} - \sum_{r=0}^{n} s_{ir} b_r \end{array}$$

where i=0……n, c_i is the input of the subsystem i, b_i is output k_{gi} is the external input and s_{ir} are constant matrices. If we define b=$[b_1^T \dots \dots \dots b_n^T]^T$,$\tilde{S}$ =$[S_{ir}]$ and we define e, e_c similarly the interconnected system can be represented by

$$k = k_c - \tilde{s}b$$

*****Formula explanation with example

Symmetries can be introduced into interconnected systems by having same subsystem dynamics and information structure. Consider interconnecting systems using star-shaped symmetry. Starting with the basic system Σ0, a collection of systems Σi connect to it without interconnections. Consequently,

$$\tilde{S} = [S \cdots u \vdots \ddots \vdots d \cdots s]$$

Theorem: Let us consider a(E,F,G) − dissipative system Σ_0 extended by m star-shaped symmetric (e, f, g)−dissipative subsystems Σi. The whole system is asymptotically stable if

$$m < \min\left(\frac{\varphi(\dot{E})}{\underline{\varphi}\,(d^T r d + \delta(\dot{e}^T - u^T G u)^{-1} \delta^T)}, \frac{\dot{e}}{u^T G u} \right)$$

where

$\dot{E}$= $-N^T GN + PN + N^T P^T$ -E>0

$\dot{e}$ = $-n^T gn + pn + n^T p^T$

$\delta = Pu + d^T P^T - N^T Gu - d^T gn$

According to the theorem, the number of subsystems that can be added to maintain stability in dissipative systems is limited. Interconnections with cyclic symmetries produce similar effects to those with star-shaped symmetries.

Passivity indices can evaluate the extent of passivity in agent interconnections, treating it as a subset of dissipation. Passivity indices for linear and nonlinear multi-agent systems with feed-forward and feedback linkages are developed using the distributed setup in [22], motivated by the need for suitable stability criteria in [21]. Linear systems use explicit passivity indices, while nonlinear systems use a series of matrix inequalities. We specialize in symmetric connectivity and provide stability results for this particular instance.

Conclusion:

This research paper, entitled "Exploring the control of cyber-physical systems through passivity, dissipation, and symmetry concepts," comprehensively explores various important facets of CPS, such as networking and the incorporation of dynamically evolving systems. Specifically, the paper investigates the stability of interconnected passive switched systems that involve both cyber and physical dynamics, considering factors such as delayed networks, event-triggered systems, and multi-agent passive systems characterized by symmetrical structures. Throughout the investigation, the principles of energy-based passivity and dissipativity emerge as vital contributors. As CPS progresses and advances, these principles will continue to play a fundamental and indispensable role in its ongoing development.

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