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Measurement and control of nonlinear dynamic systems over the internet (IoT): Applications in remote control of autonomous vehicles ☆

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ABSTRACT

This paper presents a new technique for almost sure asymptotic state tracking, stability and reference tracking of nonlinear dynamic systems by remote controller over the packet erasure channel, which is an abstract model for transmission via WiFi and the Internet. By implementing a suitable linearization method, a proper encoder and decoder are presented for tracking the state trajectory of nonlinear systems at the end of communication link when the measurements are sent through the packet erasure channel. Then, a controller for reference tracking of the system is designed. In the proposed technique linearization is applied when the error between the states and an estimate of these states at the decoder increases. It is shown that the proposed technique results in almost sure asymptotic reference tracking (and hence stability) over the packet erasure channel. The satisfactory performance of the proposed state trajectory and reference tracking technique is illustrated by computer simulations by applying this technique on the unicycle model, which represents the dynamic of autonomous vehicles.

1. Introduction

1.1. Motivations and background

In recent years, extensive research activity has been devoted to measurement and control over communication links subject to imperfections, e.g., packet dropout, distortion due to limited bandwidth, etc. Questions of this kind are motivated by future generation of mobile communications, such as 5G and tactile Internet that are explicitly intended to meet latency requirements for control applications (Fettweis, 2014; Fettweis & Alamouti, 2014). Real-time reliable data reconstruction at the end of communication links (state tracking) and stability over communication channels subject to imperfections have been an active research direction in recent years (Charalambous & Farhadi, 2008; Charalambous, Farhadi, & Denic, 2008; Cucuzzella & Ferrara, 2018; Diwadkar & Vaidya, 2013; Elia, 2004; Elia & Eisenbeis, 2011; Farhadi, 2015a, 2015b, 2017; Farhadi & Ahmed, 2011; Li & Baillieul, 2004; Liberzon & Haspanha, 2005; Liberzon & Mitra, 2016; Martins, Dahleh, & Elia, 2006; Minero, Coviello, & Franceschetti, 2013; Minero, Franceschetti, Dey, & Nair, 2009; Nair & Evans, 2004; Nair, Evans, Mareels, & Moran, 2004; Parsa & Farhadi, 2017; Quevedo & Jurado, 2017; Sanjeroon, Farhadi, Motahari, & Khalaj, 2018; Smith and Seiler, 2003; Tatikonda & Mitter, 2004a, 2004b; Vadia & Elia, 2012; Wang, Nešić, & Postoyan, 2017; Zhan, Guan, Zhang, & Yuan, 2013, 2014; Zhan, Wu, Jiang, & Jiang, 2015). Fig. 1 illustrates a basic block diagram for studying the question of real-time reliable data reconstruction and stability subject to communication imperfections. The block diagram of Fig. 1 can correspond to real applications, such as the tactile control of small autonomous vehicles (e.g. miniature drones). As these vehicles are supplied with limited capacity on-board batteries, the data from the vehicle to the remote controller (located at the control room) must be transmitted with minimum possible power; and therefore, this data transfer is subject to imperfections (e,g., packet dropout, distortion, etc.). While, the data from the control room to the vehicle can be transmitted with high power; and therefore, the transmission of data from remote controller to the vehicle can be considered almost without errors and limitations, as is shown in the block diagram of Fig. 1.

Various publications have introduced necessary and sufficient conditions for reliable data reconstruction and stability of Fig. 1, e.g., Liberzon and Haspanha (2005), Nair and Evans (2004), Nair et al. (2004) and Tatikonda and Mitter (2004a, 2004b). In most of these references, these conditions are given in the form of a

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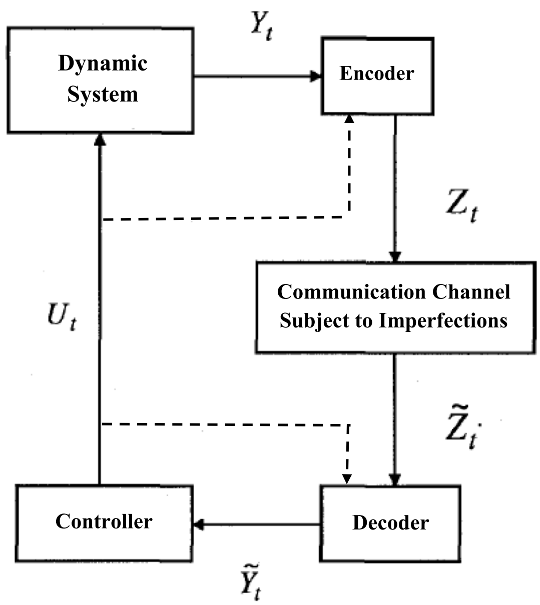

Fig. 1. A dynamic system over a communication channel subject to imperfections.

lower bound on the capacity in terms of the rate of change of dynamic system (measured in bits per time step). In particular, it is already known that the eigenvalues rate condition (i.e. $C \geq \sum_{\{i;\lambda_i(A)\geq 1\}} \log|\lambda_i(A)|$ where C is the Shannon capacity and $\lambda_i(A)$s are the eigenvalues of the system matrix A of the linear discrete time-invariant system) represents the minimum capacity under which there are encoding and stabilizing schemes for reliable data reconstruction and stability of linear time-invariant systems (Elia, 2004; Li & Baillieul, 2004; Nair & Evans, 2004; Tatikonda & Mitter, 2004a, 2004b). In this paper in addition of reliable data reconstruction and stability, we concerned with reference tracking. In Zhan et al. (2014), Zhan et al. (2013, 2015), the authors studied the optimal tracking performance of SISO linear time-invariant systems over communication channels subject to imperfections, e.g., packet dropout, induced delays. The tracking performance considered in Zhan et al. (2014) and Zhan et al., (2013) is measured by the energy of the error signal between the plant output and the reference signal. They present the explicit expressions for the minimal tracking error with or without communication constraints and show that the tracking performance depends on the non-minimum phase zeros, unstable poles and the parameters describing communication channel.

As most of important applications of networked control systems involve nonlinear systems, we study nonlinear networked control systems in this paper. In Nair et al. (2004), the authors considered the stability of a fully observed noiseless nonlinear time-invariant dynamic systems subject to unknown initial condition over the limited capacity digital noiseless channel. This problem can be modeled by the basic block diagram of Fig. 1 described by such dynamic systems and the digital noiseless channel. In Nair et al. (2004), the authors developed the notion of topological feedback entropy rate for completely deterministic system that measures the fastest rate at which the initial state information can be generated. They found a necessary and sufficient condition on the channel capacity for stability over the digital noiseless channel. In Liberzon and Haspanha (2005) the authors considered the global asymptotic stability of a fully observed continuous time-invariant nonlinear dynamic systems where the measurements must be received by controller at discrete times; and the data available to the controller is a stream of binaries. That is, they considered the control/communication system of Fig. 1 described by such nonlinear dynamic system over the digital noiseless channel; and they found a sufficient condition for stability relating the channel capacity to parameters describing the nonlinear dynamic system. Farhadi and Ahmed (2011) is concerned with tracking a vector of signal process generated by a family of distributed (geographically separated) nonlinear noisy dynamic subsystems over the packet erasure channel. Nonlinear subsystems are subject to bounded external disturbances. Measurements are also subject to bounded noises. For this system and channel, subject to constraints on transmission rates, cross over probabilities and the Lipschitz constants, a simple technique is presented ensuring tracking state trajectory with bounded mean absolute error. In Liberzon and Mitra (2016), it is shown that the desired estimation of a nonlinear systems with limited information is impossible for bit rates which are lower than the so-called estimation entropy. Furthermore, it is proved that the derived upper bound on the estimation entropy matches the average bit rate that guarantees the desired estimation. In Diwadkar and Vaidya (2013), the authors presented a necessary condition for mean square exponential reliable data reconstruction of noiseless nonlinear dynamic systems over the real erasure channel in terms of erasure probability and positive Lyapunov exponents. In Vadia and Elia (2012), the authors also presented a necessary condition in terms of the positive Lyapunov exponents for the stability of nonlinear noiseless dynamic systems over the real erasure channel. In Sanjeroon et al. (2018), a necessary and sufficient condition for real-time reliable data reconstruction of noiseless nonlinear dynamic systems over Additive White Gaussian Noise (AWGN) channel is presented. Parsa and Farhadi (2017) present a new technique for mean square asymptotic reference tracking of nonlinear dynamic systems over AWGN channel. The nonlinear dynamic system considered in Parsa and Farhadi (2017) has periodic outputs to sinusoidal inputs and is cascaded with a bandpass filter acting as encoder. The authors in Quevedo and Jurado (2017) also studied the stability problem of nonlinear constrained systems over the real erasure channel subject to random dropouts and delays. In Wang et al. (2017), the authors designed state tracker for nonlinear networked control systems over the FlexRay. Cucuzzella and Ferrara (2018) present a second order sliding mode control algorithm for a class of nonlinear systems subject to matched uncertainties. The design objective is to reduce data transmission as much as possible over a network subject to loss, jitter and delays, while guaranteeing satisfactory performance in terms of stability and robustness.

1.2. Paper contributions

The above literature review reveals that the previous works on measurement and control of nonlinear systems over communication channels subject to imperfections are limited to state tracking and/or stability for the digital noiseless channel (Liberzon & Haspanha, 2005; Nair et al., 2004), AWGN channel (Parsa & Farhadi, 2017; Sanjeroon et al., 2018), the real erasure channel (e.g., Diwadkar & Vaidya, 2013; Quevedo & Jurado, 2017) or the nonlinear Lipschitz dynamic systems (e.g., Farhadi & Ahmed, 2011). Nevertheless, recently the problem of state tracking, stability and in particular reference tracking of autonomous vehicles (miniature drones, autonomous road vehicles and autonomous under water vehicles) becomes important. Dynamic of these systems can be represented by the unicycle model (Farhadi, Domun, & Canudas de Wit, 2015), which is more complicated to be described by the Lipschitz systems. Also, it is customary to use WiFi for the tactile control of these vehicles, in which this type of communication is modeled by the packet erasure channel with feedback acknowledgment for the miniature sized vehicles. Hence, this paper addresses the problem of state tracking, stability and in particular reference tracking of the nonlinear systems over the packet erasure channel with feedback acknowledgment, as is shown in Fig. 2.