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Neural-network based approach on delay-dependent robust stability criteria for dithered chaotic systems with multiple time-delay

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A novel approach is proposed in this study to eliminate the chaotic motion by a fuzzy controller and an appropriate dither. First, a back-propagation (BP) neural-network (NN) model is used to approximate the multiple time-delay chaotic system. Then, a linear differential inclusion (LDI) state-space representation is established for the dynamics of the NN model. Based on the LDI state-space representation, this study proposes a delay-dependent stability criterion derived in terms of Lyapunov's direct method to guarantee that the trajectories of the multiple time-delay chaotic (MTDC) system under fuzzy control can be steered into a periodic orbit. Subsequently, the stability condition of this criterion is reformulated into a linear matrix inequality (LMI). According to the LMI, a fuzzy controller is then synthesized to tame the multiple time-delay chaotic (MTDC) system. If the fuzzy controller cannot suppress the chaos, a high frequency signal, commonly called dither, is simultaneously injected to eliminate the chaotic motion by regulating the dither's parameters. If the frequency of dither is high enough, the trajectories of the dithered chaotic system and its corresponding mathematical model-the relaxed system can be made as close as desired. This make it possible to obtain a rigorous prediction of the dithered chaotic system's behavior by establishing the relaxed system. Finally, this study provides a numerical example of the Chen's chaotic system with simulations to illustrate the concepts discussed throughout this paper.

1. Introduction

Nowadays, there exists a specific interest to the study of dynamical systems with chaotic behavior [1]. Chaotic behavior is abundant both in nature and in man-made devices and has been extensively demonstrated in the last few years; see for example [2–5] and the references therein. Chaos is an irregular, seemingly random, dynamic behavior of a deterministic system displaying extreme sensitivity to initial conditions [6]. Moreover chaos is occasionally desirable, but usually not expected as it can degrade performance and limit the operating range of many physical devices [7]. Therefore, in recent years much research has been focused on controlling chaos [8–19]. After the pioneering work of Ott, Grebogi and Yorke (OGY) [9], many related methods were proposed, such as the modified OGY methods [11,17], the occasional proportion feedback (OPF) or conventional linear feedback methods [12–16], entrainment and migration control techniques [8,10], etc. The OGY and its modified methods convert chaotic motion into that of the congruous unstable periodic orbit by applying small, time-dependent perturbations to a system parameter. The OPF and conventional linear feedback methods are used to control a chaotic system with a trial and error feedback gain, and the system remains nonlinear. The entrainment and migration control techniques manipulate the system trajectory to transfer one attractor to another by a switching controller [20].

Due to the unique merits in solving complex nonlinear system identification and control problems, neural-network-based modeling has become an active research field in the past few years. Neural networks (NN) consist of simple elements operating in parallel; these elements are inspired by biological nervous systems. As in nature, the connections between elements largely determine the network function. A neural network can be trained to perform a particular function by adjusting the values of the connections (weights) between elements. Therefore, a nonlinear system can be approximated as closely as desired by an NN model via repetitive training. Neural network (NN) algorithms have also been used successfully for a widely variety of applications [21]. For example, Limanond et al. [22] applied neural networks to optimal etch time control design for a reactive ion etching process. Enns and Si [23] advanced an NN-based approximate dynamic programming control mechanism for helicopter flight control. In this study, a back-propagation (BP) NN model is used to approximate the multiple time-delay chaotic (MTDC) system. The back-propagation algorithm is the most commonly used type of the neural network architecture for supervised learning because it is based on the weight error correction rules. The back-propagation

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algorithm has the advantages of simplicity and relatively simple implementation [24].

Since the work of Mamdani [25] was proposed in 1974, fuzzy control has been an active research topic. Fuzzy control design is composed of three important stages: (I) knowledge base design, (II) Control tuning parameters and (III) membership functions. In order to make the fuzzy controller achieve the prospective target, we have to adjust these three stages of the fuzzy controller [26]. Fuzzy controllers are rule-based, and implement human operator's linguistic control strategies to control processes without their exact mathematical models [27]. Due to this advantages, fuzzy control has widely been used in a variety of practical industrial applications in the past decades [28]; see, for example: Wang et al. [29] presented a new measurement system which comprises a model-based fuzzy logic controller, an arterial tonometer and a micro syringe device for the noninvasive monitoring of the continuous blood pressure wave form in the radial artery; The good tracking performance control scheme, a hybrid fuzzy neural-network control, for nonlinear motor-toggle servomechanism was given in Wai [30]; Hwang et al. [31] developed the trajectory tracking of a car-like mobile robot using network-based fuzzy decentralized sliding-mode control; A hybrid fuzzy-PI speed controller for permanent magnet synchronous motor was proposed in Sant and Rajagopal [32]; Tung et al. [33] dealt with the unbalanced vibration problem of a stabilized active magnetic bearing (AMB) system. A fuzzy gain tuning mechanism was added to adjust the output of the PID controller in order to overcome the disturbances and suppress the unbalancing vibration; An indoor intelligent service mobile robot that can locate position, avoid obstacles, use image recognition, and grip the target object was developed in Chung et al. [34]. The main focus of it is to establish a precise relative position localization system.

In recent years, there have been significant research efforts devoted to stability analysis and systematic design (see [35–37]). Moreover, the existence of modeling errors is a potential source of instability for control designs based on the assumption that the fuzzy model exactly matches the nonlinear plant [38]. And some useful approaches to overcome the influence of modeling error in the field of model-based fuzzy control for nonlinear systems have been proposed by Kiriakidis [38], Chen et al. [39,40] and Cao et al. [41,42].

The stability analysis and stabilization of time-delay systems are problems of considerable theoretical and practical significance, and have attracted the interest of many investigators for several years. Time delay often appears in various engineering systems [43], such as the structure control of tall buildings, large-scale structure systems, hydraulics, or electronic networks. The existence of delay is frequently the cause of poor performance and instability [44,45]. Consequently, the problem of stability analysis in time-delay systems remains a major topic of researchers wishing to inspect the properties of such systems. The stability criteria of time-delay systems so far have been approached in two main ways according to the dependence upon the size of delay. One method is to contrive stability conditions that do not include information on the delay, while the other method takes time delay into account. The former conditions are often called delay-independent criteria, and are generally good algebraic conditions. In particular, some delay-independent stability conditions and stabilization approaches have been proposed for nonlinear time-delay systems. Results are readily available in the literature (see [43,45,46] and the references therein). However, abandonment of information on the size of time delay necessarily causes conservativeness of the criteria, especially when the delay is comparatively small [46]. Hence, this study derives a delay-dependent criteria to handle the stability problem.

Moreover, it has been long known that the injection of a high frequency signal, known as a dither, into a nonlinear system, just ahead of the nonlinearity may improve its performance (see [47–53] and the references therein). Better performance is viewed as less distortion in the system output, augmented stability, and quenching of limit cycles and jump phenomena [51]. A rigorous analysis of stability in a general nonlinear system with a dither control was given in [47]. On the basis of the relaxed method, the relaxed system can be asymptotically stabilized by regulating appropriately the dither's parameters. Mossaheb [50] pointed out that the dither of sufficiently high frequency may result in output of the relaxed system and that of the dithered system as close as desired. This makes it possible to obtain a rigorous prediction of the stability of the dithered system by establishing that of its corresponding relaxed system, provided the dither has a high enough frequency. There are also some successful applications of dithers in recent years. Feeny and Moon [3] applied dither to quench the chaos inherent to a stick-slip oscillator and showed that the discontinuity of the low-frequency behavior could be effectively removed. Moreover, Iannelli et al. [52,53] further indicated that using dither could narrow the discontinuous nonlinearities of feedback systems.

However, making use of dither to tame the multiple time-delay chaotic (MTDC) system via neural-network (NN)-based approach has not been discussed yet. Hence, a novel approach is proposed in this study to eliminate the chaotic motion by a fuzzy controller and an appropriate dither. A back-propagation (BP) neural-network (NN) model is first used to approximate the multiple time-delay chaotic (MTDC) system. Next, a linear differential inclusion (LDI) state-space representation is established for the dynamics of the NN model. According to the LDI state-space representation, a delay dependent stability criterion derived in terms of Lyapunov's direct method is proposed to ensure that the trajectories of the multiple time-delay chaotic system under fuzzy control can be steered into a periodic orbit. Subsequently, the stability condition of this criterion is reformulated into a linear matrix inequality (LMI). Based on the LMI, a fuzzy controller is then synthesized to tame the chaotic system. If the fuzzy controller cannot suppress the chaos, a dither (as an auxiliary of the fuzzy controller) is simultaneously injected to quench the chaotic motion by regulating the dither's parameters.

This study is organized as follows: Preliminary notations throughout this paper are presented in Section 2. The problem formulation is provided in Section 3. A robustness design of fuzzy control is introduced in Section 4. In Section 5, an NN-based approach to tame the chaotic system via dither and fuzzy controller is proposed. The design algorithm is shown in Section 6. In Section 7, a numerical example of the Chua's oscillator circuit is given to illustrate the feasibility of our approach. Finally, the conclusions are drawn in Section 8.

2. Nomenclature

The following notations will be used throughout this paper.

N	multiple time-delay chaotic system (see Eq. (3.1))
$\overline{N}$	closed-loop chaotic system (see Fig. 1a)
N_d	dithered plant (see Eq. (5.1))
$\overline{N}_d$	closed-loop dithered chaotic system (see Fig. 1b)
N_r	relaxed model of N_d (see Eq. (5.2))
$\overline{N}_r$	closed-loop relaxed system (see Fig. 1c)