Chaos, Solitons and Fractals 112 (2018) 116–124

Contents lists available at ScienceDirect

Chaos, Solitons and Fractals

Nonlinear Science, and Nonequilibrium and Complex Phenomena

journal homepage: www.elsevier.com/locate/chaos

Secure communication for non-ideal channel via robust TS fuzzy observer-based hyperchaotic synchronization

Navid Vafamand[a,*], Shapour Khorshidi[b], Alireza Khayatian[a]

[a] School of Electrical and Computer Engineering, Shiraz University, Iran
[b] Air Ocean Complex, Maleke_Ashtar University of Technology, Iran

ARTICLE INFO

Article history:
Received 22 May 2017
Revised 17 April 2018
Accepted 24 April 2018

Keywords:
Secure communication
Takagi–Sugeno (TS) fuzzy system
Non-ideal communication channel
Moving average filtering
Linear matrix inequality (LMI)
Hyperchaotic Lorenz system

ABSTRACT

This paper proposes a novel hyperchaotic secure communication scheme for non-ideal communication channels. The proposed approach employs Takagi–Sugeno (TS) fuzzy model and linear matrix inequality (LMI) technique to design a controller which synchronizes the hyperchaotic transmitter and receiver systems. In the presented method, only few numbers of states are needed to be transformed which is consistent with the practical limitations of a non-ideal channel and highly secure communication. Therefore, a robust fuzzy observer is proposed to estimate the other states of the transmitter at the receiver side. Furthermore, since the channel is non-ideal, H_∞ performance criterion is employed to derive robust observer and controller against the external disturbance and noise. In order to make the proposed approach more applicable, the sufficient controller and observer design conditions are formulated in terms of linear matrix inequalities (LMIs) which can be solved by convex optimization techniques. In addition, to further remove the effect of the noise on the information recovery, a moving average filter is utilized. Finally, to show the effectiveness and advantages of the proposed approach, the hyperchaotic Lorenz system is considered and the signal is analyzed at the transmitter and receiver sides. Then, the results obtained show the superiority and effectiveness of the proposed method compared with those of the existing approaches.

1. Introduction

Emerging and developing wireless communications for personal, commercial, and governmental applications indicates the necessity and importance of safe and secure communication. Since, information signals are often transferred through a public channel environment, secure communication methods become an interesting research topic in the last two decades [1]. Among such existing approaches, the security, efficiency, and low implementation cost of chaotic and hyperchaotic-based secure communications make these methods a suitable and promising technique [2,3].

Chaotic behavior is a complex unpredictable long-term behavior exists in some nonlinear deterministic systems which are highly sensitive to the initial conditions [4,5]. Furthermore, since, a chaotic signal has a spectrum similar to the white noise, it is applicable for modulation and demodulation demands [6,7]. Hyperchaotic systems generate much more dynamical behaviors compared to the chaotic systems. One of the most significant advantages of hyper-chaotic systems is that they can have two or more positive Lyapunov exponents, which obviously can increase the security by creating more intricate dynamics owing to track separation in further directions [8,9]. Benefit from the aforementioned features, the chaotic and hyperchaotic systems have been employed for several applications including multiple access, encryption, and multiple-input-multiple-output transmission. Furthermore, the hyperchaotic signals are generated simply by electronic circuits for secure communication needs [10,11].

Similar to the common spread spectrum methods, in a hyperchaos-based secure communication, the information signal is transmitted from hyperchaotic transmitter to a hyperchaotic receiver. From the mentioned similarity, one concludes that the hyperchaos-based secure communication has several important characteristics, including: I) the chaotic signals are not simply distinguished by unauthorized users. II) This approach is robust against jamming, interference, and multipath propagation effects. A successful chaos-based secure communication comprises two parts [12,13]: I) Sending message through a communication link such that the data is transferred with high security and without any attacks. II) Recovering the original data from the receiving signals. It should be noted that the main focus of this paper is on synchro-

* Corresponding author.
E-mail address: n.vafamand@shirazu.ac.ir (N. Vafamand).

https://doi.org/10.1016/j.chaos.2018.04.035

nizing hyperchaotic systems and recovering the data at the receiver side.

Several nonlinear approaches have been employed for synchronization of hyperchaotic systems, including, adaptive [6], sliding mode [14–16], backstepping [17–19], and feedback linearization [20]. However, designing the classic conventional nonlinear approaches is hard in general and is dependent to the nonlinear system [21,22]. In other words, by selecting a different hyperchaotic system, one needs to design a new synchronizing controller. Recently, Takagi–Sugeno (TS) fuzzy model-based control is a promising approach in which a nonlinear fuzzy controller is designed systematically through the Lyapunov stability theory [23–28]. In this approach, the original nonlinear system is represented exactly by a TS fuzzy model. TS fuzzy model is a fuzzy aggregation of a finite number of local state space representation. Then, based on the obtained TS model, a fuzzy controller and/or observer are designed based on the linear matrix inequality (LMI) technique [29]. Therefore, the local feedback gains of the controller and/or observer are computed via the efficient numerical convex optimization.

Recently, several TS fuzzy based controllers have been proposed to synchronize the hyperchaotic systems. In [30], a state feedback fuzzy controller is proposed for synchronization and anti-synchronization of a class of fractional order chaotic systems. The presented controller comprises a fractional order compensation controller and fuzzy scheme. In [28], a TS based synchronizer for the nominal Rikitake chaotic system is proposed. The master and slave systems are identical and no disturbance and system uncertainty exist. Therefore, it is assumed that the premise variables of the master and slave systems are equal and sufficient state-feedback controller design conditions are derived in terms of LMIs. By considering the same assumption as [31], in [32], a TS-based model predictive state-feedback synchronizer is proposed for chaotic and hyperchaotic systems. In [33], a TS-based synchronizer for complex chaotic networks with random delay is proposed. This approach utilizes the Filppov solution to derive sufficient conditions of cluster synchronization in terms of LMIs. In [34], an impulsive fuzzy model-based controller is designed for uncertain memristor-based chaotic systems. In this approach, the synchronization error is forced to converge to a pre-defined region containing the origin. In [35], a time-delayed memristor-base Chua chaotic system is considered and used for the secure transformation of image data. In this paper, a TS-based fuzzy controller comprising the states of the transmitter and the output of the receiver systems is designed. In [36], a reduced and simplified fuzzy controller for synchronization of the Lorenz–Stenflo system represented by a 2-rule TS fuzzy model is proposed. However, the synchronization methods presented in [30–36] have some drawbacks. First, in these approaches, it is assumed that the communication public channel is perfect. Consequently, the effect of a public noisy channel on the transmitted signals are not considered and not attenuated. Second, the designed controllers comprise all of the transmitter states. However, in practical applications, all of the transmitter states are not available. Therefore, it still needs more effort for designing a fuzzy model based hyperchaos synchronizer which can cope with the minimum data transformation and is robust against the non-ideal channel.

In this paper, a novel approach for hyperchaotic synchronization-based secure communication is proposed. The proposed approach is based on TS fuzzy model, parallel distributed compensation (PDC) scheme and LMI technique. In the presented method, at the transmitter side, two signals, including the encrypted signal and the chaotic system output are transmitted thorough a non-ideal noisy channel. On the receiver side, first, a robust PDC fuzzy observer is designed to estimate the states of the transmitter based on the received noisy signal and minimize the destructive effect of the noise of the channel on the estimated states. Then, a PDC fuzzy controller is designed to synchronize the receiver system based on the estimated transmitter states and those of the receiver. To design the controller, a class of hyperchaotic systems with common input matrix is considered and a so-called cancelation technique is utilized. The sufficient conditions of robust observer and controller design are derived in terms of LMIs. Contrary to the other nonlinear synchronizers, the proposed approach provides a systematic and natural design method which is applicable to a wide class of nonlinear hyperchaotic systems represented by TS fuzzy models. Furthermore, although few papers concern with the destructive effects of the channel, to the best knowledge of the authors, this is the first try to provide a TS-based observer and controller design for non-ideal channel. Therefore, this approach is more effective for practical applications of secure communication. Finally, to show the merits of the presented approach, it is applied to chaotic and hyper chaotic numerical case studies and the obtained results are compared with the existing results in the hand.

The paper is as follows: In Section 2, the hyperchaotic-based secure communication protocol and TS fuzzy representation of the master and slave systems are provided. In Section 3, the structures of fuzzy observer and fuzzy controller are given and the sufficient conditions of robust observer and controller design conditions are formulated in terms of LMIs. In Section 4, the hyperchaotic Lorenz system is given and the numerical simulation is carried out. Finally, in Section 5, some concluding remarks and suggested further research topic are highlighted.

2. Preliminaries

2.1. Secure communication based on hyperchaotic system protocol

In the hyperchaotic-based secure communication, at the transmitter side, the information signal is modulated by a hyperchaotic transmitter system. The resulting signal is directed to the transmitter and sent through the public channel. At the receiver side, by designing a proper controller, the hyperchaotic receiver system is synchronized with that of the transmitter. Finally, the modulated message signal is demodulated by the synchronized system to provide the original signal. In the following, the transmitter and receiver hyperchaotic systems are referred as master and slave system, respectively. The diagram of the secure communication is presented in Fig. 1.

In Fig. 1, the *inf* is the original information signal, *cod* is the coded signal, p_m is the encrypting hyperchaotic signal, y_m is the output of the master system which is transferred through the channel to be used for synchronization of the slave system. Furthermore, v denotes the destructive effects of the channel, including the noise and distortion. In addition, $\hat{x}_m$ is the estimation of the master system at the receiver side. Finally, by comparing the states of the slave controller with the estimated state of the master, the control input u is generated and exerted to the slave system. Consequently, the encrypting signal is made and the coded signal is de-modulated.

Due to the need of highly secure communication and the practical limitations in transforming the signals on the channel, only limited information of the master system is transferred. On the other hand, the procedure of decoding the received signal is directly affected by the synchronization problem. In other words, getting more precise information necessitates a better synchronization. Therefore, in the receiver side, an observer is designed to estimate the states of the master system. These estimated states will be used to synchronize the slave system.