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A big data inspired chaotic solution for fuzzy feedback linearization model in cyber-physical systems

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ABSTRACT

Cyber-Physical System (CPS) that integrates computational and physical capabilities has emerged as a promising topic. It interacts with physical world and humans through ad hoc communications. In contemporary, with the fast development of CPS theory and applications, CPS generates a large volume of data, which may lead its control into a chaotic status. Hence, there is a pressing demand to solve the chaotic status CPS control. To this end, the chaotic time series prediction algorithm is employed to resolve the chaotic status featured by a fuzzy feedback linearization model. Modeling the CPS under big data without taking chaotic features into account may lead to unexpected results. This is because chaotic CPS is dramatically sensitive to small disturbances or minor changes of initiators. This paper developed a CPS model in light of fuzzy feedback linearization. Further, the chaotic time prediction algorithm is applied to solve the chaotic control problem in CPS. The developed algorithm takes both tracking control problem and synchronization control problem into account. The numerical results suggest that the developed method is feasible and efficient in tracking control and synchronization of two chaotic CPS.

1. Introduction

Cyber-physical system (CPS) plays an important role in human's daily life. It rapidly expands in many science and engineering domains, including distributed energy systems, transportation systems and healthcare monitoring systems [1]. Intelligent transportation systems, smart power grids, smart homes with network of appliances, are examples of CPS applications.

CPS is an integration of computation with physical system and physical process. It is recognized as a hybrid system that contains continuous dynamic physical process and discrete computing process. It includes physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by *control, computation and communication* (3C) [2]. In contemporary, it has attracted significant research effort. A number of logical mathematical models in the open literature have been proposed and developed since it emerged. A hybrid fuzzy automata control model based on automatic verification of real-time indicator of the finite state machine was proposed. Their work has been applied on the representation of the traditional CPS with the solution of the differential and difference equation [3]. However, their work may lead to unexpected results when taking chaotic status into account. This is because the method is extremely sensitive to initial conditions [4]. Hence, it is not hard to see that chaotic CPS can not be effectively modeled by the hybrid automata model.

Chaos theory studies the behavior of dynamical systems that are highly sensitive to initial conditions, such as a famous effect that is referred to as the butterfly effect [5].

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Small differences in initial conditions, such as those due to rounding errors in numerical computation, yield widely diverging outcomes, rendering long-term prediction impossible in general [6]. In chaos studies, tracking problem, which obtains reference signal by applying control signal, and synchronization problem, in which two chaos systems with different initial conditions gradually reach one consistent trajectory, are two crucial issues [7]. In order to solve tracking and synchronization problems, a *chaotic time series prediction* (CTSP) algorithm based on numerical techniques has been proposed. This algorithm can convincingly distinguish low-dimensional chaos from randomness, and make statistical long-term predictions. For the aforementioned reasons, the CTSP theory can be ushered into the modeling of chaotic CPS. In addition, the development and evolution of CPS not only depend on the response of discrete transient events, but also relate to the response of the dynamic behavior represented by differential and difference equation [8,9]. It is ready to see that the process may lead to chaotic status. Thus, it is critical to solve the chaotic status in order to avoid deadlocks or unexpected results.

To the best of our knowledge, we develop the first analytical model to characterize the chaotic CPS by integrating the CTSP theory into a *fuzzy feedback linearlization model* (FFLM). The developed model can be applied on the analysis of both traditional and chaotic CPS.

Apart from the aforementioned, chaotic systems are very sensitive to noises and their dynamic evolution possibly deviates far from the expected trajectory even though they are perturbed by a small noise [10,11], and the traditional FFLM did not take into account that the differential and difference equation can be chaotic if it is extremely sensitive to initial conditions. Therefore, we have introduced the CTSP theory into the traditional FFLM to adapt new characteristics brought by chaos. In order to design experiments to verify the validity of the proposed model for chaotic CPS, the first leg of this work is to figure out the features which are able to characterize chaotic system.

Existing studies suggest strange attractor, which is a disorder stable motion modality with complicated stretch and twisty structure, can be a critical feature [12]. However, many different types of attractors co-exist in the phase space [13]. Hence, it is necessary to prove what kind of particular CPS can be chaotic. Unfortunately, there is seemingly total randomness in chaotic processes, even though the chaotic system is indeed deterministic. This fact makes it difficult to distinguish chaotic evolutions from stochastic processes [14]. It is not hard to see the most convenient method to verify the potential existence of chaotic CPS is to examine whether there exists stranger attractors in systems or not. Next, we verify the validity of the developed model for chaotic CPS by solving tracking and synchronization problems. These two problems are crucial issues with regard to the chaotic theory. Last but not least, we have compared the results with the traditional FFLM with the developed model in this paper to demonstrate the improvement in performance.

This work has examined the chaos under CPS and finds there exists strange attractors who control the movement of system's output, which indicates that it is chaotic. Furthermore, results have demonstrated that the proposed model can stabilize a fixed point of tracking control problem in 0.07*s*, and synchronize two chaotic CPS in 0.25*s*. Otherwise, the traditional FFLM is not feasible to solve these two problems. One plausible reason for these observations is that the details are required for the traditional model, however, it is impossible when this is chaotic. As for the proposed model, after chaotic time sequence prediction method is introduced, it can benefit from both the closed loop stability and the chaos control ability, which makes this model suitable for chaotic CPS.

The rest of the paper is organized as follows. Section 2 presents the related work and background. Section 3 demonstrates the developed model of solving the chaotic CPS. In Section 4, the numerical results has been given. We have applied the developed model on tracking control and synchronization of two chaotic CPS. Finally, this paper is concluded in Section 5.

2. Related work

CPS has been brought to us recently. It is a promising but immature theoretical system. In open literature, research works characterized CPS features by developing CPS models. Unfortunately, most of existing works on modeling CPS are based on conventional fuzzy control theories. For instance, in [15], it has proposed an event-driven monitoring framework for CPS based on the hybrid automata formalism using an FFLM. The framework combines model-based design and formal analysis, aiming at monitoring the status in the system development stage. It is worth noting that modeling the continuous behavior of a CPS using an ordinary differential equation is difficult. This is because it may include unknown or unpredictable variables. Bogdan et al. developed a hybrid neural network and fuzzy control for automatic generation control in power systems [16]. In their work, recurrent neural network is employed to forecast control and future output of the system based on the current *area control error* (ACE) and the predicted change-of-ACE. It is not hard to see the dynamic quality of a CPS can be improved by adapting control performance standard to the fuzzy controller design. Zhang's work reveals that the system with hybrid fuzzy neural controller enhances a better stability than that of non hybrid fuzzy neural controller.

Apart from the popularity of CPS, a large volume of data generated by itself may throw the system into chaos. Recently, how to solve chaotic CPS has drawn much attention. For this reason, chaotic time sequence prediction theory has been widely applied to chaos control. Misir et al. has studied a new methodology employing chaotic time series to model chemical sensor observations in embedded phase space [17]. This method adopted a long-term prediction of sensor baseline and drift based on *phase space reconstruction* (PSR) and *radial basis function* (RBF) neural network. PSR can record all of the properties of a chaotic attractor and clearly show the motion trace of a time series. Thus PSR becomes an enabler of the long-term drift prediction using RBF neural network. The numerical results demonstrate that the proposed model can make long-term and accurate prediction of chemical sensor baseline and drift time series. Chen and Han proposed a new multivariate radial basis functions neural network model to predict the complex chaotic time series [18]. The mutual information method and false nearest-neighbor method have