Predictor-Based Load Frequency Control for Large-Scale Networked Control Power Systems

Jianwei Xia, *Member, IEEE*, Xiaoxiao Guo, Ju H. Park, *Senior Member, IEEE*, Guoliang Chen, and Xiangpeng Xie, *Senior Member, IEEE*

***Abstract*—This paper investigates the load frequency control scheme for the large-scale networked power system with large delays, where the system states are unmeasurable. A matrix dimension transformation method is proposed to solve the problem of matrix dimension mismatch caused by the complex structure of the system in the controller design process. Two formal results are demonstrated. The first result studies the exponential stability using the backstepping-based partial differential equation (PDE) method in the continuous-time control framework. The second result examines the exponential stability based on the the reduction-based ordinary differential equation (ODE) method in the framework of sampled-data control. A two-sided mode-dependent loop-based Lyapunov-Krasovskii functional is constructed so that the information of sampled-data intervals can be utilized more sufficiently. Meanwhile, with the help of proposed method, the design algorithms of controllers are given base on two predictor methods, respectively. And H_∞ performance indexes reflecting the system robustness under load-frequency control are given. The validity of the proposed methodology is verified in the simulation section using a three-area interconnected large-scale power system.**

***Index Terms*—Decentralized control, large-scale networked control systems, predictor methods, sampled-data networked control.**

I. Introduction

MODERN power systems are characterized by complex operating environments and high operational requirements. Faced with the increasing pressure of safe operation, many power systems are developed towards large scale, which in turn are modeled as large-scale power systems [1]. However, the large scale development of power systems increases the uncertainty and coupling of the system, which leads to the design of load frequency control (LFC) schemes for large-scale power systems are more complex than those for single-input single-output systems [2], [3]. Therefore, it is a practical and challenging task to design the load frequency control scheme of large-scale power systems to satisfy the required economic, safety and performance demands [4], [5].

In recent years, advanced sensor, communication and control technology have been gradually applied to large-scale power systems [6]. Large-scale networked control power system (LSNCPS) transmits drive data over a shared communication network, enabling increased system flexibility and maintainability, reduced costs and less wiring [7], [8], [9], [10]. In addition, the H_∞ performance index can effectively reflect the robustness of the system and test the interference immunity of the system under different LFC schemes [11]. Scholars have proposed many LFC schemes for dealing with input delays in power systems [12], [13], [14]. [15] proposed two relaxation negative determinant lemmas to derive the negative determinant condition of the quadratic function with delays. Some results have been obtained by scholars for large-scale power systems with small delays [16]. However, there are few results for large delays that need to be compensated in LSNCPS. To effectively compensate for large delays, [17] used a decentralized predictor to study large-scale interconnected systems which have large delays, allowing this system to achieve exponential stability. Significantly, due to the high coupling and complex dynamic characteristics of LSNCPS, it is more difficult to apply prediction methods to compensate for large delays [18], [19].

In practical applications, the system states usually are unavailable due to disadvantageous operating conditions. It is necessary to use the available measurement outputs to design observer to estimate the system states [20], [21]. Particularly, a LFC method based on dynamic state estimation was presented in [22], which used an unknown input observer for real-time dynamic tracking. However, the above-mentioned literature only considered the stability analysis of large-scale power systems without considering the design of controllers, which are difficult to apply in practical LFC control. Moreover, due to the physical limitations of exchanging information between the subsystems under LFC [23], it is much more difficult to obtain controller design algorithms with applying prediction methods.

Manuscript received 26 March 2023; revised 23 August 2023 and 14 November 2023; accepted 4 January 2024. Date of publication 9 January 2024; date of current version 21 August 2024. This work was supported in part by the National Natural Science Foundation of China under Grants 62373178, 61973148, in part by the Research Fund for the Taishan Scholar Project of Shandong Province under Grants tstp20230629 and tsqn202211174, and in part by Shandong Provincial Natural Science Foundation under Grant ZR2021JQ23. The work of Ju H. Park was supported by the National Research Foundation of Korea (NRF) funded by the Korea Government Ministry of Science and ICT, South Korea, under Grant 2019R1A5A8080290. Paper no. TPWRS-00418-2023. *(Corresponding author: Ju H. Park.)*

Jianwei Xia, Xiaoxiao Guo, and Guoliang Chen are with the School of Mathematics Science, Liaocheng University, Liaocheng 252000, China (e-mail: njustxjw@126.com; 1710500590@qq.com; chenguoliang3936@126.com).

Ju H. Park is with the Department of Electrical Engineering, Yeungnam University, Kyongsan 38541, South Korea (e-mail: jessie@ynu.ac.kr).

Xiangpeng Xie is with the Institute of Advanced Technology, Nanjing University of Posts and Telecommunications, Nanjing 210023, China (e-mail: xiexiangpeng1953@163.com).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TPWRS.2024.3351724.

Digital Object Identifier 10.1109/TPWRS.2024.3351724

H_∞ Adaptive Sliding-Mode Control for Nonlinear Delayed Singular Systems Under Impulsive Attacks via Piecewise Auxiliary Functions Method

Guangming Zhuang, Yiqun Liu, Xiangpeng Xie, *Senior Member, IEEE*, and Jianwei Xia, *Member, IEEE*

***Abstract*—This work addresses the issue of H_∞ adaptive sliding-mode control (SMC) for nonlinear delayed singular systems (NDSSs) under impulsive attacks (IAs). The NDSSs subjected to IAs are modeled as fuzzy delayed singular impulsive systems (FDSISs), and a neoteric fuzzy integral sliding surface function is constructed based on the piecewise auxiliary functions method, which is continuous on $(0, +\infty)$ without any other additional conditions. Then, a suitable SMC law and an adaptive SMC law are designed, such that the state trajectories of FDSIS can be driven to the predetermined sliding surface in finite time. In addition, an improved impulse-time-dependent Lyapunov–Krasovskii functional containing characteristics of IAs and time delays is designed, and it is demonstrated to be continuous along the FDSIS trajectories. Improved conditions are put forward in the form of strict linear matrix inequalities via congruent transformation technology, which can guarantee that the singular sliding-mode dynamics under IAs fulfills H_∞ stochastic admissibilization. Finally, the practicability of the approach presented is attested and the effects of IAs on convergence time are testified by the networked truck–trailer system.**

***Index Terms*—Adaptive sliding-mode control (SMC), impulsive attacks (IAs), nonlinear singular systems (SSs), Takagi–Sugeno (T–S) fuzzy technology, time delays.**

I. Introduction

RECENTLY, singular systems (SSs) have been significantly investigated on the grounds of their superiority in a myriad of fields, including biological systems, spaceflight engineering, and so on [1], [2]. It is important to note that the research for SSs is far more intricate than the study of normal space ones on account of the admissibility and control problem of SSs must take into account not only stability but also regularity and nonimpulsiveness/causality [3], [4]. Fortunately, many pivotal works on SSs have been reported so far, see, [5], [6], [7], [8], and so on.

On the other hand, with the evolution and development of communication technologies, various dynamic systems usually involve large-scale networks with particular interactions [9], [10]. Networked configurations typically offer the advantages of energy efficiency, flexibility, and information sharing [11]. However, open environments can give rise to a range of security problems arising from cyber-attacks, which can adversely affect the stability of the considered systems and severely impact economic and industrial equipments [12]. Typically, denial-of-service (DoS) attacks and deception attacks are the two most common types of attacks [13]. The former leads to unavailability of data from sensors and controllers, which makes transmission time delays or packet loss in signal transmission [14]. The latter refers to situations where attackers are able to access the systems and tamper with control commands and measurement data [15]. Impulsive attacks (IAs), as a special type of deception attacks, can cause instantaneous change in the systems states and deteriorate systems performances [16], [17], [18]. A significant amount of results have emerged to deal with the effects of IAs, such as [19] proposed a piecewise dynamic gain approach, which can greatly expand the class of switched linear systems with parameter uncertainty; [20] presented a neoteric Lyapunov function, which can guarantee finite nonweighted L_2 gain for asynchronously switched systems.

When SSs are subjected to external IAs from malicious attackers, singular impulsive systems (SISs) come to the fore naturally [21]. Although the results of research on impulse systems have proliferated in recent decades, there have been few studies on SISs. It should be noted that admissibilization for SISs is a very difficult and challenging task, since it is not only necessary to overcome the adverse impacts of IAs from attackers but also to eliminate the affects of internal impulses [22], [23].

As time goes on, Takagi–Sugeno (T–S) fuzzy systems have attracted widespread interest for their superiority in approximating and disposing nonlinear systems and have been broadly employed in fields of hydraulic turbine governing systems, vehicle engineering, circuit systems, etc. [24], [25],

Manuscript received 7 February 2024; accepted 25 May 2024. Date of publication 12 June 2024; date of current version 20 August 2024. This work was supported in part by the National Natural Science Foundation of China under Grant 62173174, Grant 62373178, Grant 61773191, and Grant 62103175; in part by the Discipline With Strong Characteristics of Liaocheng University–Intelligent Science and Technology under Grant 319462208; in part by the Shandong Provincial Natural Science Foundation under Grant ZR2021JQ23; in part by the Liaocheng University Education Reform Project under Grant G2023023; and in part by the Graduate Education High-Quality Curriculum Construction Project for Shandong Province under Grant SDYKC20185. This article was recommended by Associate Editor T. Li. *(Corresponding author: Xiangpeng Xie.)*

Guangming Zhuang, Yiqun Liu, and Jianwei Xia are with the School of Mathematical Sciences, Liaocheng University, Liaocheng 252059, Shandong, China (e-mail: zgmtsg@126.com; liuyiqun1998@163.com; njustxjw@126.com).

Xiangpeng Xie is with the School of Internet of Things, Nanjing University of Posts and Telecommunications, Nanjing 210023, China (e-mail: xiexiangpeng1953@163.com).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TSMC.2024.3406523.

Digital Object Identifier 10.1109/TSMC.2024.3406523

Aperiodic Sampled-Data H_∞ Control of Vehicle Active Suspension System: An Uncertain Discrete-Time Model Approach

Guoliang Chen, Guixiang Du, Jianwei Xia, *Member, IEEE*, Xiangpeng Xie, *Senior Member, IEEE*, and Zhichuang Wang

***Abstract*—In this article, the matter of aperiodic sampled-data H_∞ control of a quarter vehicle active suspension system with time-varying delay is investigated based on an uncertain discrete-time model. This article mainly solves three problems based on the theory of integral quadratic constraints. First, the system is discretized by resorting to lifting technique, the uncertainties of the discrete-time model are embodied by the operators related to sampled-data and time delay, in this process, a new norm upper bound estimation of operator is given. Second, based on the multipliers of the operator, the conditions for the improved H_∞ performance constraints are given. Third, with regard to controller design, the difficulties posed by the nonlinear coupling terms for solving the matrix inequalities are addressed by an iterative algorithm. Finally, the simulation platform and a practical example show that the proposed method is effect and can obtain more optimized results.**

***Index Terms*—H_∞ control, aperiodic sampled-data, time-varying delay, uncertain discrete-time model, vehicle active suspension.**

Manuscript received 7 September 2023; revised 22 November 2023; accepted 5 January 2024. Date of publication 24 January 2024; date of current version 4 April 2024. This work was supported in part by the National Natural Science Foundation of China under Grant 62373177, Grant 12226311, Grant 12226305, Grant 62003154, and Grant 61973148, in part by the Higher Education Institution of Shandong Province Youth Innovation Team Program under Grant 2022KJ108, in part by the Young Experts of Taishan Scholar Project under Grant tsqn202211174, in part by the Shandong Provincial Natural Science Foundation under Grant ZR2021JQ23, and in part by the Guangyue Young Scholar Innovation Team of Liaocheng University under Grant LCUGYTD2022-01. Paper no. TII-23-3444. *(Corresponding author: Guoliang Chen.)*

Guoliang Chen, Guixiang Du, and Jianwei Xia are with the School of Mathematics Science, Liaocheng University, Liaocheng 252000, P. R. China (e-mail: chenguoliang3936@126.com; duguixiang2017@163.com; njustxjw@126.com).

Xiangpeng Xie is with the Institute of Advanced Technology, Nanjing University of Posts and Telecommunications, Nanjing 210023, P. R. China (e-mail: xiexiangpeng1953@163.com).

Zhichuang Wang is with the School of Intelligence Science and Technology, the Institute of Artificial Intelligence, University of Science and Technology Beijing, Beijing 100083, China (e-mail: wangzhichuang@ustb.edu.cn).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TII.2024.3353856.

Digital Object Identifier 10.1109/TII.2024.3353856

I. Introduction

Vehicle suspension, that is treated an important device to transfer and filter the force between road surface and vehicle body, has played a major role in improving the vehicle performance [1]. Generally speaking, the main performance requirements include: eliminating the swaying impact caused by rough road surface to passengers (ride comfort); ensuring the firm maintain and uninterrupted contact of wheels to road (driving safety), restricting suspension travel and hydraulic actuator. Unfortunately, these requirements are conflicting and difficult to be optimized at the same time. As a control approach to tradeoff these performance requirements, active suspension system has received more and more attention in recent decades [2], [3].

A lot of work has been carried out to improve the performance of active suspension system, such as finite time control [4], fuzzy control [5], and event-triggered adaptive control [6], [7]. In the control of active suspension system, disturbance is a nonnegligible factor that destroys the stability and the performance of the system. As a control method that can estimate and reduce the influence of disturbance on the system and optimize the system performance, H_∞ control has been favored by many researchers [8], [9], [10], [11], [12], [13]. The multiobjective H_∞ control problem of automobile suspension system was studied in [8] and [9] by using the classical input delay method and stochastic system approach, respectively. In [11] and [12], the H_∞ performance was used to measure ride comfort and different performance requirements were given in different forms, which avoided the conservatism brought by constraining all requirements in a single objective function. Furthermore, the H_∞ performance constraint in frequency band was considered in [13]. In summary, how to establish performance constraints more optimally and how to estimate performance more accurately with the system uncertainty is an topic worth exploring.

In recent years, with the proliferation of computer and digital control technology, more and more attention has been paid to sampled-data control, which enables the design of digital controllers in continuous-time system [14], [15]. Besides, due to the inevitable problems, such as data transmission delay, packet loss, and data timing disorder in actual applications, the packet transmission intervals are aperiodic, making the control method of aperiodic sampled-data control of great interest, and there are many mature research outcomes, such as input delay

Reinforcement Learning-Based Adaptive Event-Triggered Fuzzy Control for Cyclic Switched Stochastic Nonlinear Systems With Actuator Faults

Chengyuan Yan, Jianwei Xia, *Member, IEEE*, Ju H. Park, and Xiangpeng Xie, *Senior Member, IEEE*

***Abstract*—In this article, the adaptive fuzzy optimized tracking control problem of uncertain cyclic switched stochastic nonlinear systems with actuator faults and prescribed performance is studied under average cycle dwell time. For achieving a better optimal control strategy, the information of the switching signal is taken into account by the reinforcement learning algorithm of the identifier-critic-actor architecture. Meanwhile, a novel mode-dependent event-triggered optimized mechanism for subsystem is proposed to resolve the impact of asynchronous switching on system performance, which not only does not have strict assumptions but also reduces the communication burden. Moreover, to eliminate the impact caused by actuator failures, fault-tolerant compensation scheme depending on the switching signal is designed. By presenting Lemma 3 and using the coordinate transformation technique, it is proven that the choice of the performance index function still conforms to the control protocol under the prescribed performance control framework. In the optimized backstepping control design, the proposed controller is able to ensure that all signals in the closed-loop system are bounded in probability and tracking error meets performance. Finally, both numerical and practical simulations are given to illustrate the effectiveness of the proposed optimization scheme.**

***Index Terms*—Cyclic switched system, event-triggered mechanism, fault-tolerant control, fuzzy logic system, reinforcement learning.**

I. Introduction

The uncertain problem of nonlinear systems has received great attention. In order to solve the influence of uncertainty on system performance, the adaptive control method has been widely used and has achieved a series of excellent results [1], [2], [3], [4]. For dealing with the unknown dynamics of nonlinear systems, neural network (NN) [5], [6] and fuzzy-logic system (FLS) [7], [8], [9], [10] have been proven to be the effective techniques. Meanwhile, with the progress of science and technology, the requirement of tracking accuracy and the behavior of predetermined tracking transient are more and more important. To guarantee the requirement of system performance, the prescribed performance control (PPC) scheme was proposed in [11]. Since then, the PPC has been a popular topic for a large number of researchers and has achieved remarkable works, including the infinite-time PPC in [12] and the finite-time PPC in [13], respectively. Nevertheless, in the process of control design, the above adopted PPC method implementation is associated with initial conditions of the system tracking error. The set-time performance function was used to solve the above problem of convergence rate, which implied that the convergence time to a specified domain can be arbitrarily set in [14]. A novel control method that can achieve preassignable tracking precision within the prescribed time was presented in [15], whose prescribed function is independent of tracking error.

With the rapid development of industry and the large amount of energy consumption, how to save energy has become the research focus of modern control theory. Under this background, optimal control comes into being. Optimal control is to guide the system to achieve control objectives by searching for control protocols, while minimizing cost function, thereby achieving a balance between system performance and resource consumption [16]. Reinforcement learning (RL) is widely used in optimal control because it does not need to establish the exact mathematical model between environment and task, and has fast reactivity and high adaptability. A novel identifier-critic-actor architecture of RL was designed to handle the unknown prior knowledge of nonlinear function for uncertain nonlinear system in [17]. Although optimization techniques have been well developed in control theory, it is a pity that the above control schemes are not directly applicable to backstepping control. In [18], a control technique named optimized backstepping (OB) was proposed for a class of strict-feedback nonlinear systems whose essence was derived from the solution of the Hamilton–Jacobi–Bellman (HJB) equation to get the minimum cost function. Subsequently, there were many excellent results using the OB method [19], [20], [21]. More specifically, in [19], a simplified OB control

Manuscript received 12 June 2023; revised 23 August 2023; accepted 18 September 2023. Date of publication 26 September 2023; date of current version 1 March 2024. This work was supported in part by the National Natural Science Foundation of China under Grant 62373178 and Grant 61973148, in part by the Research Fund for the Taishan Scholar Project of Shandong Province of China under Grant tstp20230629, in part by Shandong Provincial Natural Science Foundation under Grant ZR2021JQ23, and in part by the Open Project of Liaocheng Universtiy Animal Husbandry Discipline, China under Grant 319312101-01. The work of Ju H. Park was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT) under Grant 2019R1A5A8080290. Recommended by Associate Editor G. Feng. *(Corresponding authors: Jianwei Xia; Ju H. Park.)*

Chengyuan Yan and Jianwei Xia are with the School of Mathematics Science, Liaocheng University, Liaocheng 252000, China (e-mail: 1205603762@qq.com; njustxjw@126.com).

Ju H. Park is with the Department of Electrical Engineering, Yeungnam University, Kyongsan 38541, Republic of Korea (e-mail: jessie@ynu.ac.kr).

Xiangpeng Xie is with the Institute of Advanced Technology, Nanjing University of Posts and Telecommunications, Nanjing 210023, China (e-mail: xiexiangpeng1953@163.com).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TFUZZ.2023.3319316.

Digital Object Identifier 10.1109/TFUZZ.2023.3319316

Finite-Time Command Filtered Control for Multiagent Systems With Unknown Control Gains and Quantized Inputs

Yu Gao, Wei Sun, *Senior Member, IEEE*, Shun-Feng Su, *Fellow, IEEE*, and Xudong Zhao, *Senior Member, IEEE*

***Abstract*—The problem of finite-time consensus tracking is investigated for multiagent systems with unknown control gain functions and hysteresis quantized inputs. Existing control methods utilizing command filtered technique have certain limitations for unknown control gains. Motived by this, the study is concerned with establishing a novel control strategy based on a modified command filtered technique with estimation-like terms and key compensation terms. Furthermore, fuzzy logic systems participate in command filter design while processing unknown items. It is theoretically testified that the proposed scheme not only guarantees the finite-time consensus tracking performance but also remains that all the resulting closed-loop signals are bounded. Finally, the simulations on numerical and practical examples prove the validity of the control scheme.**

***Index Terms*—Command filtered technique, finite-time consensus tracking, fuzzy logic systems (FLSs), hysteresis quantized inputs, unknown control gains.**

I. Introduction

THE MULTIAGENT systems (MASs) are complex systems consisted of multiple subsystems. Each subsystem not only has certain computing and perception abilities for the environment but also can share information with each other. Such MASs are applied to cooperate on complex tasks that a single subsystem cannot effectively accomplish. Based on the above superiority, MASs have been applied to many aspects, such as unmanned aerial vehicles [1], formation of mobile robots [2], communication among sensor networks [3], etc. At present, many scholars have focused their attention on the research of MASs and made many achievements in consensus tracking problems [4], formation control problems [5], attack problems [6], and so on. For the consensus tracking problem, an effective adaptive control protocol is put forward in [4], in which compensation terms and positive integrable functions are introduced in virtual control design. The proposed recursive design approach for asynchronously switched followers is more general in [7], because it does not need to know the signs of the control gains. Moreover, the consensus tracking problems on discrete-time MASs [8] and fractional-order MASs [9] are studied. In fact, some fields prefer to complete the objective within a finite time. To quickly achieve the control goal, the relevant theory of finite time is applied to MASs [10], [11], [12], [13], [14]. Among them, the fault-tolerant control problem for systems with output dead zones is processed in [10]. The case where the input of leader is bounded is considered in [11], and the case where the input of leader and state derivatives are bounded is further investigated in [12]. These studies promote the development of MASs.

In the field of engineering, nonlinear systems are often employed to describe practical controlled systems, and backstepping is adopted to deal with issues of them. As we all know, fuzzy logic systems (FLSs) are combined to adaptive control to deal with uncertainty issues. Currently, this approach has been used in a variety of systems, for example, large-scale systems [15], switched systems [16], MASs [17], and actual systems [18]. Among them, Li and Yu [15] proposed a decent method that uses output sampling data on large-scale interconnected systems, and Yang et al. [17] put forward a valid transformation function to handle state-constrained and unconstrained systems. During the backstepping design process, the virtual controllers are repeatedly differentiated, so as the system order increases, the "explosion of complexity" issue arises. In response to the above problem, Swaroop et al. [19] proposed dynamic surface control (DSC) technique and the key of DSC is to add first-order filters. Compared with DSC, the tracking differentiator constructed by Liu et al. has lower complexity in [20]. Later, Farrell et al. proposed the command filtered technique in [21] where suitable compensation signals are designed to solve the influence of filter errors that DSC does not take into account. The problem of consensus tracking is solved by the command filtered technique for the first time [22]. Then, the finite-time command filter is introduced

Manuscript received 2 January 2023; revised 23 June 2023; accepted 1 July 2023. Date of publication 26 July 2023; date of current version 17 October 2023. This work was supported in part by the China Postdoctoral Science Foundation under Grant 2022M721902, and in part by the Guangyue Young Scholar Innovation Team of Liaocheng University under Grant LCUGYTD2022-01. This article was recommended by Associate Editor T. Li. *(Corresponding author: Wei Sun.)*

Yu Gao and Wei Sun are with the School of Mathematics Science, Liaocheng University, Liaocheng 252000, China (e-mail: gaoyu5160@126.com; sunw8617@163.com).

Shun-Feng Su is with the Department of Electrical Engineering, National Taiwan University of Science and Technology, Taipei 106, Taiwan (e-mail: sfsu@mail.ntust.edu.tw).

Xudong Zhao is with the Faculty of Electronic Information and Electrical Engineering, Dalian University of Technology, Dalian 116024, China (e-mail: xdzhaohit@gmail.com).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TSMC.2023.3292287.

Digital Object Identifier 10.1109/TSMC.2023.3292287

Chaos, Solitons and Fractals 175 (2023) 114044

Contents lists available at ScienceDirect

Chaos, Solitons and Fractals

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

Stability analysis of a cart-pendulum model with variable convergence rate: A sliding mode control approach for impulsive stochastic systems

Yuanen Li [a], Huasheng Zhang [a,*], Xiangpeng Xie [b], Jianwei Xia [a]

[a] School of Mathematical Sciences, Liaocheng University, Liaocheng, Shandong 252059, PR China
[b] Institute of Advanced Technology, Nanjing University od Posts and Telecommunications, Nanjing, Jiangsu 210023, PR China

A R T I C L E I N F O

Keywords:
Sliding mode control
Variable convergence rate
Interval-driven
Impulsive stochastic systems

A B S T R A C T

In this paper, a sliding mode control problem with variable convergence speed for impulsive stochastic systems based on the cart-pendulum model is investigated. Firstly, the cart-pendulum is modeled as impulsive stochastic system and the interval-driven stability criterion for variable convergence rate is given according to the idea of pole configuration. Meanwhile, the corresponding sliding mode surface functions are designed by pre-adjusting the intervals which in turn regulate the convergence rate of the target system states. To attenuate the oscillation phenomenon that exists in the sliding mode control, the new continuous control rate function is designed on the basis of the saturation function. In addition, a sliding mode control strategy for impulsive stochastic systems is presented to ensure the reachability of the designed sliding surface in finite time and the stability of the reduced-order system under motion of the sliding mode. Finally, the cart-pendulum simulation results demonstrate the effectiveness and feasibility of the sliding mode control.

1. Introduction

Cart-pendulum systems [1,2] are characterized by their multi-variable, non-linear, unstable, and fast dynamic response, making them popular in the field of control. Current research in car-pendulum balance control is primarily focused on verifying the effectiveness of algorithms in handling these complex systems. For example, [3] has proposed an adaptive robust combination of feedback linearization and sliding mode controller based on fuzzy rules and gradient descent law to control a car pendulum system. The literature [4] has designed a reliable sampling controller with deceptive attacks to ensure asymptotic stability, which has verified in a cart-pendulum system. This validation of the ability of the control method to handle complicated systems advances the evolution of modern control theory.

As a classical type of hybrid systems, impulsive systems have received a wide range of attention in the field of control. The presence of impulsive phenomena in system poses challenges to research, yet also enhances its practical significance. Examples include pulse-like electric shocks (voltage or current) often used in electronic devices [5], timed treatments in pharmacokinetics [6], the predetermined capture of populations [7], the closing of switches [8], etc. Impulsive stochastic systems (ISSs) [9–12] are commonly used in the control field to model such phenomena. Therefore, ISSs modeled on the basis of cart-pendulum systems can not only portray mathematical models of real problems with sudden changes or disturbances, but can also take full account of the influence of abrupt factors on the state of these systems, which can accurately reflect the laws and characteristics of the changes themselves.

Sliding mode control (SMC) is a nonlinear robust control technique that aims to move the controlled object to a pre-designed sliding mode surface within a finite time frame. Once on the surface, the states of the target system are maintained on the desired trajectory to the equilibrium point via high frequency switching control, based on which stochastic stabilization or exponential stabilization of a particular system is effectively achieved [13–15]. SMC has become an increasingly popular area of research due to its complete robustness to matching disturbances, simple design method, ease of implementation, and fast response for system motion, see [16,17]. As a result, SMC has found a wide range of applications in fields such as robotics [18], mechanical engines [19], aerospace [20], servo systems [21], power systems [22], and more. Significant progress has been made in the design of linear sliding surfaces. Specifically, in Ref. [23], the pole configuration method has been used to design sliding mode parameters. This approach has since been extended to the design of sliding mode surfaces for linear multivariable systems in [24]. The analysis shows that the sliding phase eliminates the need to consider system disturbances, and the SMC is highly robust to matching disturbances.

* Corresponding author.
E-mail addresses: yuanenli0418@163.com (Y. Li), zhanghuasheng@lcu.edu.cn (H. Zhang), xiexiangpeng1953@163.com (X. Xie), njustxjw@126.com (J. Xia).

https://doi.org/10.1016/j.chaos.2023.114044
Received 25 May 2023; Received in revised form 11 August 2023; Accepted 8 September 2023
Available online 16 September 2023

H_∞ Control With Convergence Rate Constraint for Time-Varying Delay Switched Systems

Yalin Deng, Huasheng Zhang, and Jianwei Xia, *Member, IEEE*

***Abstract*—This article emphasizes the H_∞ control problem with convergence rate constraint for time-varying delay switched systems under the average dwell time switching signal. First, a novel criterion of asymptotic stability with H_∞ performance is advanced by introducing the method of average dwell time and the definition of asymptotic interval stability, which is more exact than the general stability criterion in estimating the convergence of the systems. Next, the technique of structuring H_∞ controller is derived from the stability analysis described above, which can constrain the rate of the system to equilibrium, and make it content the preset H_∞ performance. Finally, a numerical calculation and a water pollution control issue demonstrate the functionality of the technique.**

***Index Terms*—Average dwell time (ADT), convergence rate, H_∞ control, time-varying delay switched systems (TVDSSs).**

I. Introduction

HYBRID systems are made up of continuous dynamic systems and discrete dynamic systems governed by differential equations. One of the principal kinds of hybrid systems is the switched system (SS), which comprises limited subsystems and has a logical rule to coordinate the switching between subsystems. In recent decades, SSs have caused considerable concentration as a result of their intrinsic characteristics and wide applications domain, such as electronic power system [1], air traffic control system [2], robot control system [3], hot metal processing system [4], and so on. Theoretically speaking, many amusing fruits have been acquired in SSs [5], [6], [7], [8], [9].

In practical engineering control, it is noted that the natural phenomenon of time-varying delay is inescapable in kinds of real-world applications, such as chemical reactor delayed system [10], circuit system [11], network control system [12], etc. Simultaneously, time-varying delay can impinge the regular working and the prevenient performance criteria. Hence, it is very significant to draft some techniques to handle the impact of time-varying delay. Then, some positive results have been achieved in the problem of time-varying delay SSs (TVDSSs) to surmount these weaknesses. Take [13] for instance, the design problem of asynchronous resilience controller for a class of nonlinear TVDSSs with uncertainty in a preset finite-time interval is investigated. Luo et al.[14] devoted to the new methods for stability analysis of stochastic TVDSSs. The robust finite-time guaranteed cost control of impulsive TVDSSs is focused on [15]. Li et al. [16] highlighted observer-based output feedback control for neutral TVDSSs via an event-triggered sampling programme. In [17], fault-tolerant control for a class of uncertain TVDSSs under average dwell time (ADT) is raised.

Furthermore, the presence of disturbances input often results in instability and performance regression and other cacoethic performances of the system. Over the past two decades, H_∞ control policy has been universally deployed in stability analysis and control synthesis for systems dealing with disturbances input [18], [19], [20], [21], [22]. Combined with the accomplishments of H_∞ control policy and TVDSSs, the H_∞ control problem of TVDSSs has been diffusely regarded. For example, [23] considered the asynchronous H_∞ control issue for TVDSSs. Ma et al. [24] resolved the finite-time H_∞ control problem of TVDSSs on account of event-triggered scheme. The exponential H_∞ control problem for a class of nonlinear TVDSSs is underlined in [25]. Li et al. [26] devoted itself to the discussion of event-triggered observer-based H_∞ control of TVDSSs. In [27], finite-time H_∞ sliding mode control of discrete TVDSSs is investigated.

What attracts more attention is the precise control of the system, extraordinarily the constraint on the rate of system convergence to equilibrium, which has also received special attention from scholars in recent years. For linear systems, the restriction on the eigenvalue distribution of the state matrix can meet both dynamic and steady performance of the system. Pole placement is a significant way to settle such problems [28], [29]. The promotion of interval stability as a pole placement has also attracted much interest recently [30], [31], [32], [33]. Among them, [30] handled the interval stability and stabilization of stochastic linear systems (SLSs) via spectrum technology. Sun and Xu [31] advocated the exponential stability and interval stability of singular SLSs. Zhang et al. [32] developed the interval stability criterion for time-varying delay SLSs. Zhang et al. [33] concentrated on solving the problem of L_2–L_∞ filter design for time-varying delay SLSs in view of filtering speed constraints. Although the above literature works give interval stability conditions for various systems, it is noteworthy that the H_∞ control problem with interval stability constraint about TVDSSs has not been thoroughly focused on. Inspired by the aforementioned literature, the expectation

Manuscript received 6 February 2023; accepted 12 July 2023. Date of publication 10 August 2023; date of current version 20 November 2023. This work was supported in part by the Shandong Provincial Natural Science Foundation under Grant ZR2021JQ23, and in part by the Natural Science Foundation of Shandong Province under Grant ZR2022MF293. This article was recommended by Associate Editor X. Zhao. *(Corresponding author: Huasheng Zhang.)*

The authors are with the School of Mathematics Science, Liaocheng University, Liaocheng 252000, Shandong, China (e-mail: dengyalin0315@163.com; zhsh0510@163.com; njustxjw@126.com).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TSMC.2023.3298813.

Digital Object Identifier 10.1109/TSMC.2023.3298813

H_∞ Asynchronous Admissibilization for Nonlinear Singular Delayed Hybrid Hydraulic Turbine Governing Systems With Impulsive Perturbations

Yiqun Liu, Guangming Zhuang, Xiangpeng Xie, *Senior Member, IEEE*, and Jianwei Xia, *Member, IEEE*

***Abstract*—This article researches H_∞ asynchronous admissibilization for nonlinear singular delayed hybrid hydraulic turbine governing systems with impulsive perturbations. By exploiting Takagi–Sugeno fuzzy technique, the fuzzy singular delayed hybrid hydraulic turbine governing system with impulsive perturbations is built, which cannot only accurately and concisely describe the dynamic behaviors of the pipeline, but also resist damages for the hydraulic turbine system caused by sudden reasons. Then, the asynchronous fuzzy state-feedback controller (FSFC) is designed by using parallel distributed compensation technique, and the asynchronous mechanism between the modes of FSFC and the modes of controlled plant is depicted by a hidden Markovian model. By constructing an improved timer-dependent Lyapunov–Krasovskii functional, the new criteria about H_∞ admissibilization for fuzzy singular delayed hybrid hydraulic turbine governing systems with impulsive perturbations can be acquired. The gains of asynchronous FSFC are expressed by solving linear matrix inequalities. Impulsive operators are successfully generalized and extended from $\mathbb{R}$ to $\mathbb{R}^{n\times n}$, which makes the approach presented in this article more universal. Finally, the simulation results prove the correctness and availability of the method provided in this article.**

***Index Terms*—H_∞ admissibilization, asynchronous fuzzy control, hidden Markovian model (HMM), impulsive perturbations, singular delayed hybrid hydraulic turbine governing systems (HTGSs).**

I. Introduction

As sustainable power generation strategies have received increasing attention in recent decades, hydropower has become an increasingly important player in the world's energy strategies [1], [2]. As is known to us, the hydraulic turbine governing systems (HTGSs) are one of the most important links of hydropower station, and their operating situations directly influence the stable operation of the hydroelectric station [3], [4]. Therefore, the modeling, analysis as well as control problems of HTGSs have become hot topics of research among scholars [5]. In recent years, many researchers have tried to build nonlinear models of HTGSs [6]. However, most of them treated the delayed algebraic equations approximately, and only few scholars considered the delayed singular property [7]. Therefore, for the sake of describing the dynamic behaviors of the pipeline more accurately as well as to be more consistent with practical engineering, the delayed singular property of the pipeline is considered in this article.

In the recent decades, singular systems have played a significant role in many fields, such as aircraft modelings, cross-linking systems, power systems, and missile systems [8], [9]. According to different application fields, singular systems are described as constrained systems, descriptor variable systems, semistate systems, and so on [10], [11]. In contrast to regular systems, singular systems have the advantages that they can keep the construction of physical systems, portray dynamic, and static constraints [12].

It is worth noticing that the admissibility (including stability, nonimpulsiveness/causality, and regularity) has to be considered for singular systems while the latter two problems do not exist for the regular systems [13], [14]. So, the control of singular systems is considerably more difficult and intricate than that of regular case [15], various research results on the admissibility analysis, sliding-mode control, filtering, feedback control for singular systems have proliferated, see, e.g., [16], [17], [18], [19].

On the other hand, impulsive systems have gained widespread interest due to their extensive applications in communication networks, control technology, engineering sciences, biology, and other fields [20], [21]. Generally speaking, from the perspective of impulse effects, impulsive systems can be studied in terms of impulsive perturbations and impulsive control [22]. The former describes systems subjected to transient disturbances at discrete moments, where transient disturbances impulses can deteriorate system performances and may lead to instability [23]. The latter corresponds to the case where the intermittent control impulses can stabilize the unstably controlled system and improve system performances [24].

Manuscript received 17 April 2023; accepted 19 May 2023. Date of publication 23 May 2023; date of current version 1 December 2023. This work was supported in part by the National Natural Science Foundation of China under Grant 62173174, Grant 61973148, and Grant 61773191, in part by the Shandong Provincial Natural Science Foundation under Grant ZR2021JQ23, in part by the Discipline with Strong Characteristics of Liaocheng University–Intelligent Science and Technology under Grant 319462208, in part by the Support Plan for Outstanding Youth Innovation Team in Shandong Higher Education Institutions under Grant 2019KJI010, in part by the Graduate education high-quality curriculum construction project for Shandong Province under Grant SDYKC20185.
(Corresponding authors: Guangming Zhuang; Xiangpeng Xie.)

Yiqun Liu, Guangming Zhuang, and Jianwei Xia are with the School of Mathematical Sciences, Liaocheng University, Liaocheng 252059, China (e-mail: liuyiqun1998@163.com; zgmtsg@126.com; njustxjw@126.com).

Xiangpeng Xie is with the Institute of Advanced Technology, Nanjing University of Posts and Telecommunications, Nanjing 210023, China (e-mail: xiexiangpeng1953@163.com).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TFUZZ.2023.3279294.

Digital Object Identifier 10.1109/TFUZZ.2023.3279294

Adaptive Asymptotic Tracking Control for Flexible-Joint Robots With Prescribed Performance: Design and Experiments

Le Wang, Wei Sun, *Senior Member, IEEE*, Shun-Feng Su, *Fellow, IEEE*, and Xudong Zhao, *Member, IEEE*

***Abstract*—This study reports the adaptive asymptotic tracking control problem for flexible-joint (FJ) robot systems, the output tracking error can be kept within the prescribed range in the initial stage of system operation, as time approaches infinity, the asymptotic tracking result can be obtained. The prescribed performance function and the positive integrable time-varying function are introduced simultaneously in the control design of FJ robot systems for the first time. The control scheme is designed under the frame of the adaptive backstepping method and command filtered technique, which successfully avoids the problem of complexity explosion. The radial basis function neural networks are used to deal with unknown uncertainties and the adaptive laws are designed to approximate the norms of weight vectors and approximation errors. Finally, the feasibility of the proposed scheme is proved by the simulation and the experiment of the 2-link FJ robot on the Quanser platform.**

***Index Terms*—Adaptive backstepping control, asymptotic tracking, flexible-joint (FJ) robots, prescribed performance.**

I. Introduction

With the development of robotics, flexible robots have received more and more attention [1], [2], [3], [4], [5] as they are flexible and can perform more complex work than rigid robots can not achieve. Flexible robots are divided into flexible-joint (FJ) robots and flexible-link robots. Among them, FJ robots have been developed rapidly owing to the advantages of high speed, low energy consumption, low production costs, and strong adaptability, so they are widely used in industry, aerospace, medical, and other aspects. For FJ robots, the commonly used modeling methods include the Kane equation method, the Lagrange equation method, and the Newton–Euler equation method. Therein, the Lagrangian method is based on the principle of energy balance, and is more suitable for systems with relatively high system complexity. On this basis, Spong models the FJ robot and proposes a simplified dynamic model [6]. Then, a lot of breakthroughs have been made in the study of FJ robot systems [7], [8], [9]. In [7], a robust control method is proposed based on Spong's model for FJ robots and ensures that all signals are uniformly ultimately bounded. Besides, the study in [10] models a singularly perturbed model to solve the control problem for FJ robot systems.

For control methods of the FJ robot systems, there are mainly adaptive backstepping control [11], singular perturbation control [12], sliding-mode control [13], and so on. Among the above control methods, the adaptive backstepping control is a valid method to design adaptive controller, especially for nonlinear systems with the lower triangular form. A backstepping control scheme is proposed in [14] for FJ servo systems. The global output feedback tracking control problem for FJ robots is solved by combining the backstepping control in [15]. However, the "complexity of explosion" cannot be ignored in the design of adaptive backstepping control, which means the computational burden brought by the derivative of the virtual controllers as the dimension of system increases. Fortunately, Dong et al. [16] proposed an adaptive backstepping control implementation approach based on the command filtered, thereby avoiding differentiation of the virtual controllers. Subsequently, many excellent results [17], [18], [19] have been obtained by using this method. For example, the command-filtered technique is successfully applied to the FJ robot systems and the desired control goals are achieved in [17] and [18]. In addition, we all know that there exist some unknown uncertainties in nonlinear systems, FJ robot systems are no exception. When the uncertainty is not solved, the performance of the system will be seriously affected. With the development of intelligent control, approximating uncertain terms through fuzzy logic systems (FLSs) or neural networks (NNs) has become an effective control method of FJ robot systems [20], [21], [22].

It must be emphasized that the most of above-mentioned results have achieved a practical tracking effect. To make the system output track the desired signal more accurately, this study investigates the problem of asymptotic tracking control. Compared with practical tracking control, the latter can guarantee that the tracking error converges to zero instead of a

Manuscript received 4 October 2022; accepted 15 December 2022. Date of publication 2 January 2023; date of current version 18 May 2023. This work was supported in part by the Natural Science Foundation of Shandong Province for Key Projects under Grant ZR2020KA010; in part by the China Postdoctoral Science Foundation under Grant 2022M721902; and in part by the "Guangyue Young Scholar Innovation Team" of Liaocheng University under Grant LCUGYTD2022-01. This article was recommended by Associate Editor S. S. S. Ge. *(Corresponding author: Wei Sun.)*

Le Wang and Wei Sun are with the School of Mathematics Science, Liaocheng University, Liaocheng 252000, China (e-mail: wangle9909@163.com; sunwei@lcu.edu.cn).

Shun-Feng Su is with the Department of Electrical Engineering, National Taiwan University of Science and Technology, Taipei 106, Taiwan (e-mail: sfsu@mail.ntust.edu.tw).

Xudong Zhao is with the Faculty of Electronic Information and Electrical Engineering, Dalian University of Technology, Dalian 116024, China (e-mail: xdzhaohit@gmail.com).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TSMC.2022.3230703.

Digital Object Identifier 10.1109/TSMC.2022.3230703

Chaos, Solitons and Fractals 169 (2023) 113289

Contents lists available at ScienceDirect

Chaos, Solitons and Fractals

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

Intelligent control of convergence rate of impulsive dynamic systems affected by nonlinear disturbances under stabilizing impulses and its application in Chua's circuit

Xuezhen Wang, Huasheng Zhang *

School of Mathematical Sciences, Liaocheng University, Liaocheng, Shandong 252059, PR China

ARTICLE INFO

Keywords:
Impulsive dynamical linear systems
Stabilizing impulses
Variable convergence rate stability
Variable convergence rate stabilization
Time-varying delay

ABSTRACT

This paper investigates the variable convergence rate stability and variable convergence rate stabilization of impulsive dynamic linear systems with stabilizing impulses affected by nonlinear disturbances. The eigenvalues (poles) of the system state are closely related to the convergence or divergence rate of the system. Sufficient conditions for the variable convergence rate stability are obtained by using the generalized pole placement idea and the method of system transformation. By designing a memoryless state feedback controller, sufficient conditions of variable convergence rate stabilization are obtained, ensuring the asymptotic stability of the target closed-loop system and accurately adjusting the system state's convergence rate. An algorithm for adjusting the speed of system state convergence and its flow chart are designed by referring to the C programming language. Combined with the variable convergence rate stabilization method, the intelligent control of system state convergence speed is realized at the operation level. As a representative example of chaotic systems, Chua's circuit affected by impulses verifies the effectiveness of the variable convergence rate stabilization method.

1. Introduction

As a special kind of hybrid systems, impulsive dynamic linear systems (IDLSs) are usually composed of an impulse law, an ordinary differential equation, and a difference equation. These systems have some characteristics of both discrete and continuous dynamical systems, and their states often jump at the moment of impulse occurrence. In the real world, IDLSs have a wide range of applications in aerospace, economy, ecological population, pharmacokinetics, and other fields [1–5].

At present, stability analysis still plays an indispensable role in the research of IDLSs. Scholars have conducted profound and fruitful studies on the asymptotic stability, exponential stability, input–output stability, and finite-time stability of IDLSs [6–14]. It is interesting to note that the above stability studies rarely involve the system's dynamic indicators, such as the response time and the convergence speed of the system state. This aroused the authors' interest and attention.

Although the stability conditions mentioned above can make the corresponding closed-loop system state converge in the existing system, the convergence speed is either too fast or too slow, which is often undesirable. The state convergence speed of IDLSs is expected to reach the desired level, and no excessive control input is expected.

In articles [15–17], interval stability and stabilization have been researched, and the close relationship between the system's poles and the system state's convergence rate is revealed. Inspired by the above studies, this paper explores and proposes the variable convergence rate stability and stabilization of IDLSs with stabilizing impulses affected by nonlinear disturbances. Through system transformation and the generalized pole assignment, sufficient conditions for the variable convergence rate stability (VCRS) are obtained by designing and changing the driving parameters. Further, by designing a state feedback controller, the sufficient conditions for the variable convergence rate stabilization (VCRSN) is obtained. VCRSN can precisely adjust the convergence speed of IDLSs state, and its effectiveness is verified by applying a Chua's circuitaffected by impulses [18–20]. The main contributions of this paper include four parts:

1. The new concepts of VCRS and VCRSN are proposed, and the VCRS can not only ensure the stability of the target system but also reflect the convergence speed of the system.

2. The VCRSN can ensure the asymptotic stability of IDLSs with stabilizing impulses and accurately adjust the corresponding closed-loop system state's convergence speed (SSCS) so that the SSCS can reach the desired level. The effectiveness of its accurate regulation of the SSCS

* Corresponding author.
E-mail addresses: wangxuezhen8668@163.com (X. Wang), zhsh0510@163.com (H. Zhang).

https://doi.org/10.1016/j.chaos.2023.113289
Received 6 November 2022; Received in revised form 12 February 2023; Accepted 17 February 2023
Available online 3 March 2023

Robust Sampled-Data Control for Switched Complex Dynamical Networks With Actuators Saturation

Guoliang Chen, Jianwei Xia, *Member, IEEE*, Ju H. Park, *Senior Member, IEEE*, Hao Shen, *Member, IEEE*, and Guangming Zhuang

***Abstract*—In this article, an aperiodic sampled-data control problem is investigated for polytopic uncertain switched complex dynamical networks subject to actuator saturation. Due to the constraint on the upper bound of the sampling interval being no greater than the dwell time, the issue concerning the asynchronization between the sampled-data controller mode and the system mode is hence considered to be caused by subsystems that may switch in a sampling interval. By considering the sampling interval without switching and the sampling interval with switching, the parameters-dependent loop-based Lyapunov functionals are constructed, respectively. With the help of the constructed functional, mean-square exponential stability criteria for the error polytopic uncertain switched complex dynamical networks are presented under the definition of average dwell time. Furthermore, based on the stability criteria, the asynchronous aperiodic sampled-data controller is designed for polytopic uncertain switched complex dynamical networks subject to actuator saturation. The polytopic uncertain switched complex dynamical networks can be guaranteed to exponentially synchronize with the target node based on the proposed stability conditions and aperiodic sampled-data controller design method. Finally, by transforming the proposed theoretical conditions into the LMI-based objective optimization problem, the domain of attraction of polytopic uncertain switched complex dynamical networks is estimated. An example based on switched Chua's circuit is applied to verify the effectiveness of the proposed method.**

***Index Terms*—Actuator saturation, complex dynamical networks, mean-square exponential stability, robust sampled-data control.**

Manuscript received 30 January 2021; accepted 25 March 2021. Date of publication 20 April 2021; date of current version 16 September 2022. This work was supported in part by the National Natural Science Foundation of China under Grant 62003154, Grant 61973148, and Grant 61773191; and in part by the Natural Science Foundation of Shandong Province for Outstanding Young Talents in Provincial Universities under Grant ZR2016JL025. The work of Ju H. Park was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MSIT) under Grant 2020R1A2B5B02002002. This article was recommended by Associate Editor F. Wu. *(Corresponding authors: Jianwei Xia; Ju H. Park.)*

Guoliang Chen, Jianwei Xia, and Guangming Zhuang are with the School of Mathematics Science, Liaocheng University, Liaocheng 252000, China (e-mail: chenguoliang3936@126.com; njustxjw@126.com; zgmtsg@126.com).

Ju H. Park is with the Department of Electrical Engineering, Yeungnam University, Kyongsan 38541, South Korea (e-mail: jessie@ynu.ac.kr).

Hao Shen is with the School of Electrical and Information Engineering, Anhui University of Technology, Maanshan 243002, China (e-mail: haoshen10@gmail.com).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TCYB.2021.3069813.

Digital Object Identifier 10.1109/TCYB.2021.3069813

I. Introduction

DUE TO the rapid growth in the size and complexity of dynamical systems, more research has focused on the modeling and control of complex dynamical networks. Complex networks are widely used in many aspects of real life, for example, the nervous system can be seen as a network formed by a large number of nerve cells connected to each other through nerve fibers, and a computer network can be seen as a network formed by autonomously working computers connected to each other through communication media. Similarly, there are power networks, social relationship networks, transportation networks, dispatch networks, and so on [1]–[6]. As an important research content of complex dynamical networks, a large number of research results around the synchronization problem of complex dynamical networks have been presented. Reference [7] verifies that the synchronization of time-varying complex dynamical networks depends on the eigenvalues and eigenvectors of the internal coupling matrix and the network coupling configuration matrix. Pinning impulsive controllers were designed for the synchronization of stochastic complex dynamical networks in [9]. A state observer-based complex dynamical networks was presented in [10] so that a scalar coupled signal achieved the network synchronization. Applying the hybrid discontinuous adaptive control and impulsive control technique, synchronization problems of delayed complex dynamical networks with different nodes and random disturbances were considered in [11]. By designing impulsive controllers that do not rely on sign functionality and do not cause chattering, the fixed-time synchronization problem of complex dynamical networks was solved in [12]. Considering fixed topology and dynamic topology, with fixed and unfixed controllers, the synchronization problem under different settings is unified analyzed in [13]. Combining algebraic graph theory and Lyapunov theory to analyze the asymptotic convergence of error complex dynamical networks, an adaptive distributed controller based on the fuzzy-logic system is designed to realize the synchronization of complex dynamical networks in [14]. The adaptive synchronization control of complex dynamical networks with actuator faults and unknown coupling weights was investigated in [15]. In addition, especially in [16] and [17], a detailed research method is given for the problem of actuator saturation in complex dynamical networks.

$\mathcal{L}_2 - \mathcal{L}_\infty$ Filter Design With Adjustable Convergence Rate for Linear Stochastic Systems

Huasheng Zhang, Jianwei Xia, *Member, IEEE*, Ju H. Park, *Senior Member, IEEE*, Hao Shen, *Member, IEEE*, and Jun Chen

***Abstract*—The $\mathcal{L}_2 - \mathcal{L}_\infty$ filter design for linear stochastic time-varying delay systems based on the filter velocity constraint is considered in this dissertation. Different from existing $\mathcal{L}_2 - \mathcal{L}_\infty$ performance analysis and filter design, a new criterion is proposed to make a more accurate judgment, which can not only guarantee the stability of the filtering error system with $\mathcal{L}_2 - \mathcal{L}_\infty$ performance level but also can estimate the convergence speed of the filter. The ideal filter should has the same convergence speed as the original system, so as to ensure the rapid convergence of the error system, but also not to reduce the anti-interference ability and increase the bandwidth of the filter system. By the new filter design method, an ideal filter can be designed, which can regulate the convergence speed of the filter system to the desired effect. A simulation instance is provided to exhibit the validity of the new approach.**

***Index Terms*—Asymptotic mean square stability, interval stability, $\mathcal{L}_2 - \mathcal{L}_\infty$ filter.**

I. Introduction

Linear stochastic time-varying delay systems (LSTDSs) have been widespread concern received extensive attention on account of their extensive practical application background, such as chemical process, biological system, machine driven system, financial system, population model, and network control system. A large quantity of results on LSTDS has been addressed in the past few decades, such as various stability analysis and control [1]–[5], robust control [6], [7], H_2/H_∞ control [8]–[10], and H_∞ filter and $\mathcal{L}_2 - \mathcal{L}_\infty$ filter [11]–[13].

Manuscript received 15 February 2021; revised 12 June 2021; accepted 27 January 2022. Date of publication 11 February 2022; date of current version 16 September 2022. This work was supported in part by the National Natural Science Foundation of China under Grant 61973148 and Grant 62173165; in part by the Open Project of Liaocheng Universtiy Animal Husbandry Discipline under Grant 319312101-01; and in part by the National Research Foundation of Korea (NRF) Grant funded by the Korea Government MSIT under Grant 2020R1A2B5B02002002. This article was recommended by Associate Editor Q. Ge. *(Corresponding authors: Jianwei Xia; Ju H. Park.)*

Huasheng Zhang and Jianwei Xia are with the School of Mathematics Science, Liaocheng University, Liaocheng 252000, Shandong, China (e-mail: zhsh0510@163.com; njustxjw@126.com).

Ju H. Park is with the Department of Electrical Engineering, Yeungnam University, Kyongsan 38541, Republic of Korea (e-mail: jessie@ynu.ac.kr).

Hao Shen is with the School of Electrical and Information Engineering, Anhui University of Technology, Ma'anshan 243002, China (e-mail: haoshen10@gmail.com).

Jun Chen is with the School of Electrical Engineering and Automation, Jiangsu Normal University, Xuzhou 221116, China (e-mail: jchen2019@jsnu.edu.cn).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TSMC.2022.3149514.

Digital Object Identifier 10.1109/TSMC.2022.3149514

As an important research direction in the application of the system theory, a filtering problem has been widely concerned. The Kalman filtering method is a popular way to handle the filtering problem, which is based on the given system and Gaussian noises with known statistics [14]. As more widely used filtering methods, $\mathcal{L}_2 - \mathcal{L}_\infty$ filtering and H_∞ filtering techniques can deal with unknown external interference [15]–[17].

Recently, $\mathcal{L}_2 - \mathcal{L}_\infty$ filter design for LSTDSs has received particular emphasis of a large number of scholars [18]–[25]. As a way to cut back the filter's conservative, free weighting matrix method, stochastic integral inequality, and delay-decomposition approach have been used to construct $\mathcal{L}_2 - \mathcal{L}_\infty$ filters of LSTDSs. Meanwhile, the research of $\mathcal{L}_2 - \mathcal{L}_\infty$ filter design has been extensively employed to a large amount of special systems, such as singular Markovian jump systems [13], [17], stochastic time-delay systems [18]–[21], switched systems [23], [25], and neutral systems [22], [24].

Although the above literature have given the $\mathcal{L}_2 - \mathcal{L}_\infty$ filter design scheme for various systems, there is no relevant literature to explore the convergence rate of the filters as far as we know. Motivated by the distribution of system eigenvalues and interval stability/stabilization approach [26]–[28], we are committed to exploring more detailed properties of $\mathcal{L}_2 - \mathcal{L}_\infty$ filters and improving their various performance. The interval stability conditions of the filter error system are provided, which can estimate the asymptotic mean square stability of the filtering error system and the asymptotic convergence speed. This is a significant improvement in the theoretical study of filtering problems. Then, a more accurate filter design method is addressed, which can adjust the speed of the filter.

According to the characteristics of the estimation error, when the convergence speed of the filter is faster than that of the original system, the estimation error will converge faster. However, the fast convergence speed of the filter is at the cost of increased bandwidth and reduced anti-interference ability. Meanwhile, it does not speed up the convergence of the error system, when the convergence speed of the filter is much faster than that of the original system. Without doubt, it will certainly slow down the convergence speed of the estimation error if the convergence speed of the filter is too slow.

Therefore, it is essential to construct a filter with the convergence speed of the original system. The filter design in this way will not reduce the convergence speed of the estimation error compared to the filter with slow convergence speed, nor will it need to increase the bandwidth and reduce

Chaos, Solitons and Fractals 164 (2022) 112635

Contents lists available at ScienceDirect

Chaos, Solitons and Fractals

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

Stochastic admissibility and H_∞ output feedback control for singular Markov jump systems under dynamic measurement output event-triggered strategy

Meng Sun [a], Guangming Zhuang [a,*], Jianwei Xia [a], Yanqian Wang [b], Guoliang Chen [a]

[a] School of Mathematical Sciences, Liaocheng University, Liaocheng Shandong 25205, PR China
[b] School of Information and Control Engineering, Qingdao University of Technology, Qingdao, 266520, PR China

ARTICLE INFO

Keywords:
Event-triggered control
Markov jump systems
Singular systems
Dynamic output feedback control
Stochastic admissibility

ABSTRACT

This paper investigates the stochastic admissibility and H_∞ dynamic output feedback control for singular Markov jump systems under dynamic measurement output event-triggered strategy. By applying singular value decomposition technique and constructing novel Lyapunov–Krasovskii functional based on dynamic measurement output event-triggering mechanism, improved conditions are realized such that the singular Markov jump closed-loop system satisfies stochastic admissibility and H_∞ performance index. Moreover, dynamic output feedback controller gains are obtained via linear matrix inequality technique. Finally, the serviceability of proposed methods is demonstrated by direct current motor driven load and a numerical example.

1. Introduction

Markovian jump systems (MJSs) can model hybrid systems with random disturbance or sudden structural transformations such as manufacturing systems, fault-tolerant systems, aircraft systems, networked systems, and so forth [1–4]. The studies of MJSs have important practical and theoretical implications [5–9]. Consequently, many important results on the analysis and synthesis of MJSs have been given in some literature, such as [10–14].

On the other hand, singular systems are known as differential–algebraic systems, constrained systems, degenerate systems, implicit systems, descriptor systems, or generalized state–space systems, which can reserve the structure of practical systems and describe physical systems better than normal/regular systems due to the special characteristic of differential algebraic constraints [15–17]. Lots of real systems, such as electrical network systems, power systems, robots systems, and so on, can be modeled as singular systems [18–21]. So far, many famous results of admissibility analysis (including regularity, causality/non-impulsiveness, stability), feedback control, filtering, normalization, sliding model control, and so forth, have been reported in monographs and articles; see, [22–27]. However, it is inevitable that singular systems might undergo mutations in model parameters or system structure in enormous practical applications, which arouse the study on singular Markovian jump systems (SMJSs), up to now, many famous works have been published; see, [28–32] and so on.

Recently, network systems have received much attention [33–35]. Noting that the communication load will become very large with the increasing network complexity, which will cause network blockage or network packet loss. Fortunately, the event-triggering mechanism occupies less network resources and can effectively transfer the data [36–38]. Therefore, studies of event-triggered controls have received considerable attention of many scholars and experts in recent years [39–41]. Event-triggered controls can effectively decrease the quantity of data transmitted, while maintain systems stability and anticipant performances [42–44]. Thus, a wide variety of event-triggering strategies including static event-triggering strategies and dynamic event-triggering strategies have been proposed and widely used [45–47].

Significantly, most event triggering controls are state-based event triggering controls; see, [48–50]. However, the full states information of practical systems is not easy to directly obtain or it takes a high cost. Therefore, a part of scholars began to study event triggering controls under measurement output [51–53]. Among them, [52] presented a dynamic event triggering mechanism (ETM) to design dynamic output feedback (DOF) controller and realized the superiority of relieving communication resources. [53] designed state feedback controller and investigated H_∞ control for SMJSs based on dynamic ETM. Compared with state feedback controller, the practicability and flexibility of DOF control are relatively strong in practical application, but DOF controller for SMJSs remain enormous difficulties and challenging due to differential algebra constraints and internal pulse effects [54–56]. According to the authors' limited knowledge, DOF-based dynamic event triggering control for SMJSs are still open, which motivates our investigation of this paper.

* Corresponding author.
E-mail address: zgmtsg@126.com (G. Zhuang).

https://doi.org/10.1016/j.chaos.2022.112635
Received 23 April 2022; Received in revised form 7 August 2022; Accepted 27 August 2022
Available online 14 September 2022

Adaptive Fuzzy Event-Triggered Control for High-Order Nonlinear Systems With Prescribed Performance

Wei Sun, *Senior Member, IEEE*, Shun-Feng Su, *Fellow, IEEE*, Yuqiang Wu, and Jianwei Xia, *Member, IEEE*

***Abstract*—This article focuses on the design of a novel adaptive fuzzy event-triggered tracking control approach for a category of high-order uncertain nonlinear systems with prescribed performance requirements, in which a high-order tan-type barrier Lyapunov function (BLF) is employed to handle and analyze the output tracking error, fuzzy systems are adopted to identify the totally unknown nonlinear functions, and only one gain function rather than parameter estimation functions is designed to cancel out all unknowns appearing in fuzzy systems. As a result, complicated calculations are avoided and a structured simple control is achieved. The proposed controller not only ensures that the tracking error is always within a predefined region but also reduces the communication burden from the controller to the actuator. Finally, comparison simulations are presented to verify the effectiveness of the proposed control schemes.**

***Index Terms*—Adaptive fuzzy tracking control, event-triggered control, high-order nonlinear system, prescribed performance.**

I. Introduction

Tracking control is an important issue in practical engineering [1], and many excellent control results for various systems have been made under unremitting efforts [2], [3]. Generally speaking, it can be divided into two categories according to the effect of the control objectives achieved: 1) asymptotic tracking [4], [5] and 2) practical tracking [6], [7]. The former requires that the output of the system can completely track the target trajectory, that is, the tracking error can asymptotically approach zero. The cost of achieving such a result is that more higher requirements may be needed for the controlled system. In fact, it is difficult to achieve such a goal since internal or external disturbances or aging of the structures. The practical tracking control guarantees that the tracking error is within an allowable bound. Compared with the former, practical tracking is easier to implement, so that it has attracted increasing attention.

High-order nonlinear systems are neither feedback linearization around the origin nor affine in the control input [8]; hence, their control design is one of the most challenging issues. The research of high-order nonlinear systems is also appealing because they are widely used in practical life, and an instance is a coupled underactuated mechanical system [8]. Therefore, many researchers focus on the control of the high-order nonlinear system, and a sequence of results has been achieved, for example, two different adaptive control schemes are addressed in [9] for high-order nonlinear systems with time delay. An improved finite-time control method is designed in [10]. Moreover, the problem of finite-time stabilization is extended to stochastic higher-order nonlinear systems in [11] and [12]. For complex multiple stochastic high-order nonlinear systems, the distributed cooperative control is presented in [13]. An adaptive stabilization issue is discussed in [14] for stochastic high-order nonlinear systems with stochastic inverse dynamics. In view of neural networks control, an adaptive tracking controller under arbitrary deterministic switching is proposed in [15] for stochastic switched high-order nonlinear systems. On the other hand, the studies in [16]–[20] report several practical tracking control strategies for high-order systems. It is worth emphasizing that the tracking error cannot enter the desired range until a finite moment in the literature. From the beginning of control behavior to this moment, it can only be guaranteed that tracking error is bounded but is unable to determine how big it is. Sometimes, it is needed to monitor the value of tracking error in the whole process in engineering. Inspired by control methods proposed in [21]–[24], this study continues to research practical tracking control of high-order nonlinear systems and designs a control scheme to ensure that the tracking error is always within a preset bound.

With the popularization of the network in various control systems, event-triggered control has received much

Manuscript received September 12, 2019; revised July 9, 2020; accepted September 17, 2020. Date of publication October 23, 2020; date of current version May 19, 2022. This work was supported in part by the National Natural Science Foundation of China under Grant 61973148 and Grant 62073187; in part by the Ministry of Science and Technology, Taiwan, under Grant MOST 108-2221-E-011-159; and in part by the "Center for Cyber-Physical System Innovation" from the Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education in Taiwan. This article was recommended by Associate Editor F. Wu. *(Corresponding author: Shun-Feng Su.)*

Wei Sun and Jianwei Xia are with the School of Mathematics Science, Liaocheng University, Liaocheng 252000, China (e-mail: sunw8617@163.com; njustxjw@126.com).

Shun-Feng Su is with the Department of Electrical Engineering, National Taiwan University of Science and Technology, Taipei 106, Taiwan (e-mail: sfsu@mail.ntust.edu.tw).

Yuqiang Wu is with the Institute of Automation, Qufu Normal University, Qufu 273165, China (e-mail: wyq@qfnu.edu.cn).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TCYB.2020.3025829.

Digital Object Identifier 10.1109/TCYB.2020.3025829

*p*th Moment Asymptotic Stability/Stabilization and *p*th Moment Observability of Linear Stochastic Systems: Generalized $\mathcal{H}$-Representation

Huasheng Zhang, Jianwei Xia, *Member, IEEE*, Weihai Zhang, *Senior Member, IEEE*, Baoyong Zhang, *Member, IEEE*, and Hao Shen, *Member, IEEE*

***Abstract*—This article develops a generalized $\mathcal{H}$-representation, which can transforms stochastic systems into deterministic systems. With the help of this new approach, the necessary and sufficient conditions of *p*th moment asymptotic stability and stabilization of linear stochastic systems are addressed. Meanwhile, the generalized $\mathcal{H}$-representation method is also applied to investigate *p*th moment observability and *p*th moment complete observability for the addressed systems.**

***Index Terms*—$\mathcal{H}$-representation, power vector, *p*th moment asymptotic stability, *p*th moment observability.**

I. Introduction

Stochastic systems were important in science and industry, such as finance, biology, chemical process, environment, and population model, which has become a very important research topics in control theory, see monograph [1], [2] and literature [3]–[12]. It's well known that stochastic stability is an essential concept to stochastic systems and has been widely researched over the past few decades (see [13]–[20]). In general, the stability of stochastic systems can be classified into stability in probability, mean square stability, *p*th moment stability, almost sure stability, and so on. It should be noted that the majority of current literatures were just concerned with the mean square stability (see [21]–[25]). Recently, a few reports of *p*th moment stability and stabilization for stochastic systems have been drawn a lot of attention [26]. To mention a few, Zhang and Zhang [14] studied stochastic equations in the *p*th moment sense. *p*th moment stability of stochastic nonlinear system is discussed in [15]. Xu *et al.* [17] presented the *p*th moment global exponential ultimate boundedness criteria and provided the estimated exponential convergence rate and the ultimate bound. Zhou and Luo [20] investigated *p*th moment stability by the generalized Razumikhin and Krasovskii stability approaches. However, it is noted that, just sufficient conditions were proposed in the above references.

Meanwhile, a technique named $\mathcal{H}$-representation has been proposed explicitly in [27], which is a powerful method to investigate the mean square stabilization, exact detectability, exact observability, and stochastic spectral assignment for linear stochastic systems [28]–[31]. For instance, Zhang and Chen [27] not only presented the application of the $\mathcal{H}$-representation method in matrix equations but also provided some conditions of $\mathcal{D}$-stabilization, stochastic observability, weak stability, and stabilization of stochastic systems. The conditions of stochastic stabilizability and Popov Belevith Hautus Criterion of observability for stochastic systems were obtained with the aid of unremovable spectral theorem and the $\mathcal{H}$-representation method in [28]. The infinite horizon stochastic H_2/H_∞ control noise were investigated in [29]. Zhao and Zhang [30] studied the finite-time stability and stabilization of stochastic systems. Zhao and Deng [31] established moment stability theorem for the stochastic systems with the stability properties.

Motivated by the aforementioned discussion, we will provide a generalized $\mathcal{H}$-represented method in this article. With the new technique, the state matrix could be extended to generalized form, meanwhile, the quadratic terms of the state vector in $\mathcal{H}$-representation will be extend to *p*th terms using the lexicographical order of the monomials. Then, many problems of stochastic systems can be handled directly with the classical methods in deterministic system theory. Furthermore, the technical note will focus on the *p*th moment stability/stabilization, *p*th moment observability, and *p*th moment complete observability for Itô stochastic systems by means of the new generalized $\mathcal{H}$-representation method.

We organize this article as follows. The definition of the power vector and some necessary lemmas are introduced in Section II. Section III presents some necessary and sufficient conditions of the *p*th moment stability and stabilization to the linear stochastic systems. The *p*th moment observability

Manuscript received July 20, 2019; revised November 8, 2019; accepted July 19, 2020. Date of publication August 20, 2020; date of current version January 17, 2022. This work was supported in part by the Natural Science Foundation of Shandong Province under Grant ZR2018MF028; in part by the National Natural Science Foundation of China under Grant 61573177, Grant 61973148, and Grant 61773191; and in part by the Natural Science Foundation of Shandong Province for Outstanding Young Talents in Provincial Universities under Grant ZR2016JL025. This article was recommended by Associate Editor Y. Kang. *(Corresponding author: Jianwei Xia.)*

Huasheng Zhang and Jianwei Xia are with the School of Mathematics Science, Liaocheng University, Shandong 252000, China (e-mail: zhsh0510@163.com; njustxjw@126.com).

Weihai Zhang is with the College of Electrical Engineering and Automation, Shandong University of Science and Technology, Qingdao 266590, China.

Baoyong Zhang is with the School of Automation, Nanjing University of Science and Technology, Nanjing 210094, China.

Hao Shen is with the School of Electrical and Information Engineering, Anhui University of Technology, Ma'anshan 243002, China.

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TSMC.2020.3011217.

Digital Object Identifier 10.1109/TSMC.2020.3011217

Asynchronous Feedback Control for Delayed Fuzzy Degenerate Jump Systems Under Observer-Based Event-Driven Characteristic

Guangming Zhuang, Wei Sun, *Senior Member, IEEE*, Shun-Feng Su, *Fellow, IEEE*, and Jianwei Xia, *Member, IEEE*

***Abstract*—This article is concerned with the issue of asynchronous feedback control for fuzzy degenerate jump systems with mode-dependent time-varying delays via Takagi–Sugeno fuzzy control technique under observer-based event-driven characteristic. The improved observer and event trigger transmit not only state estimate signals but also the information of Markovian jump modes to the controller under the networked nonperiodic sampling scheme. Applying parallel distributed compensation technique, the asynchronous fuzzy feedback controller is devised, and the asynchronous fuzzy controller modes are depicted by a hidden Markovian model, where the modes of fuzzy controller run asynchronously with that of the original degenerate fuzzy jump systems. Exponentially decreasing function is employed to devise the triggering threshold, which can ensure not only the admissibility of the delayed fuzzy degenerate jump systems but also the effectiveness of event-driven strategy. Original stochastic admissibility and asynchronous feedback control conditions are characterized by linear matrix inequalities. A numerical example and a single-link robot arm model are applied to illustrate the correctness and validity of the proposed observer-based event-driven asynchronous fuzzy feedback control technique.**

***Index Terms*—Asynchronous feedback control, fuzzy degenerate jump systems (FDJSs), hidden Markovian model (HMM), nonperiodic sampling, observer and event trigger design.**

I. Introduction

DEGENERATE systems (which are also referred to as singular systems, descriptor systems, implicit systems, etc.) have received much attention from the control theory and engineering application fields because a degenerate system is a more natural and clearer representation for a large number of practical dynamic systems such as mechanical systems, robotics systems, power and circuit systems, and biological and social systems [1]–[3].

Degenerate systems are represented by a family of coupled differential and algebraic equations, which are referred to as slow subsystem and fast subsystem, respectively. The fast subsystem is formulated by algebraic equations containing infinite dynamic and infinite nondynamic modes, which cause the special features of degenerate systems such as impulse behavior, input derivatives, noncausality, etc. [4]–[6].

It is worth mentioning that the admissibility has to be considered for degenerate systems, which includes regularity, nonimpulsiveness/causality, stability, etc. Thus, the investigation for degenerate systems is more complex and more difficult to control than normal/regular state-space systems. Over the last 40 years, degenerate systems have developed continuously by virtue of normal systems theory, many outstanding works in stability and admissibility analysis, feedback control, filtering, sliding mode control, etc., have been reported successively [7]–[10].

On the other hand, during the past few decades, Markovian jump systems (MJSs) have been highly heeded in control and engineering areas due to their own hybrid characteristics endowed by stochastic Markov switching/jump process [11]–[15]. During the past few decades, various kinds of stability analysis and control synthesis for MJSs have been thoroughly and profoundly investigated, such as [16]–[20] and the references therein. Degenerate systems mingle with stochastic Markovian jump features, which results in the well-known degenerate Markovian jump systems (DMJSs) [21]–[23]. Recently, DMJSs have received much attention, and many basic and important results have been reported such as admissibility and stabilization, feedback control, filter designing, passivity and dissipativity, and so on [24]–[28].

However, the most published approaches about DMJSs only limited in linear scope under the framework of singular value decomposition (SVD) and slow–fast decomposition (SFD), which are not applicable for nonlinear degenerate systems [1], [4]–[6]. So far, admissibility for nonlinear degenerate systems has not been deeply studied due to the fact that the regularity, impulsive-freeness of nonlinear degenerate system must be defined and

Manuscript received June 12, 2020; revised August 25, 2020; accepted September 24, 2020. Date of publication September 30, 2020; date of current version December 1, 2021. This work was supported in part by the National Natural Science Foundation of China under Grant 61773191 and Grant 61973148, in part by the Support Plan for Outstanding Youth Innovation Team in Shandong Higher Education Institutions under Grant 2019KJI010, in part by the Minister of Science and Technology, Taiwan, under Grant MOST 108-2221-E-011-159, and "Center for Cyber-Physical System Innovation" from The Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education (MOE) in Taiwan, in part by the Natural Science Foundation of Shandong Province for Outstanding Young Talents in Provincial Universities under Grant ZR2016JL025. *(Corresponding author: Shun-Feng Su.)*

Guangming Zhuang, Wei Sun, and Jianwei Xia are with the School of Mathematical Sciences, Liaocheng University, Liaocheng 252059, China (e-mail: zgmtsg@126.com; sunw8617@163.com; njustxjw@126.com).

Shun-Feng Su is with the Department of Electrical Engineering, National Taiwan University of Science and Technology, Taipei 106, Taiwan (e-mail: su@orion.ee.ntust.edu.tw).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TFUZZ.2020.3027336.

Digital Object Identifier 10.1109/TFUZZ.2020.3027336

Admissibilization for Implicit Jump Systems With Mixed Retarded Delays Based on Reciprocally Convex Integral Inequality and Barbalat's Lemma

Guangming Zhuang, Jianwei Xia, Jun-e Feng, Wei Sun, and Baoyong Zhang

***Abstract*—This article considers admissibility analysis and stabilization for implicit Markovian jump systems (IMJSs) with retarded discrete-distributed delays. Admissibility analysis is investigated for the unforced delay IMJSs by virtue of reciprocally convex integral inequality technique and Barbalat's lemma. State feedback controller is designed via the matrix transformation technique to realize the stabilization of the delayed closed-loop IMJSs. By selecting comprehensive L-K functional with modes and delays information, admissibilization conditions are presented in terms of LMIs. Two illustrative examples including an inverted pendulum controlled by a direct current motor (DCMCIP) system are utilized to certify the effectiveness and practicality of the admissibilization technique.**

***Index Terms*—Admissibility analysis, Barbalat's lemma, implicit Markovian jump systems (IMJSs), retarded discrete-distributed delays, state feedback control.**

I. Introduction

IMPLICIT systems are also referred to as singular systems, semistate systems, descriptor systems, degenerate systems, etc., Over the past two decades, implicit systems have been intensively investigated and lots of real fields, such as power systems, circuit systems, economic processes, robotic systems, and so on, can be modeled by implicit systems [1]–[4].

Manuscript received September 24, 2019; accepted December 26, 2019. Date of publication January 16, 2020; date of current version October 15, 2021. This work was supported in part by the National Natural Science Foundation of China under Grant 61773191, Grant 61603170, Grant 61973148, and Grant 61877036, in part by the National Natural Science Foundation for Outstanding Young Talents of China under Grant 61922044, in part by the Natural Science Foundation of Shandong Province for Outstanding Young Talents in Provincial Universities under Grant ZR2016JL025, in part by the Support Plan for Outstanding Youth Innovation Team in Shandong Higher Education Institutions under Grant 2019KJI010, in part by the Talent Introduction and Cultivation Plan for Outstanding Youth Innovation Team in Shandong Higher Education Institutions, in part by the Undergraduate Education Reform Project of higher Education in Shandong Province under Grant M2018X047, and in part by the Liaocheng University Education Reform Project Foundation under Grant G201811 and Grant 26322170267. This article was recommended by Associate Editor T. I. Strasser. *(Corresponding author: Guangming Zhuang.)*

Guangming Zhuang, Jianwei Xia, and Wei Sun are with the School of Mathematical Sciences, Liaocheng University, Liaocheng 252059, China (e-mail: zgmtsg@126.com; njustxjw@126.com; tellsunwei@sina.com).

Jun-e Feng is with the School of Mathematics and System Sciences, Shandong University, Jinan 250061, China (e-mail: fengjune@sdu.edu.cn).

Baoyong Zhang is with the School of Automation, Nanjing University of Science and Technology, Nanjing 210094, China (e-mail: baoyongzhang@njust.edu.cn).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TSMC.2020.2964057.

Digital Object Identifier 10.1109/TSMC.2020.2964057

Implicit systems are formulated as a set of coupled algebraic and differential equations, which lead to the finite dynamic modes, infinite nondynamic modes, and infinite dynamic modes. The infinite dynamic modes can cause undesired impulse, which will destroy the system performance even the stability. The analysis and control of implicit systems are much more complicated than that of normal (regular) systems because admissibility have to be considered. Admissibility includes stability, regularity, and nonimpulsiveness/causality at the same time [5], [6]. Therefore, the investigation for implicit systems has great theoretical and practical significance.

During the past three decades, implicit systems have acquired much attention. Up to now, a great deal of fundamental and important results based on the theory of regular (normal) systems have been extended successfully to implicit systems [7]–[17]. To mention a few, [7] studied H_2 output feedback control and mixed H_2/H_∞ control problems for continuous-time implicit systems via LMI approach; [5], [6], [8], [9] investigated robust control and H_∞ filtering for implicit systems with discrete or distribution delays; [2], [11] researched H_∞ control and stabilization for implicit systems based on strict LMI; [12] addressed optimal control for stochastic implicit systems; [13]–[15] dealt with guaranteed cost control and robust normalization for implicit systems; [16] provided synthesis problem of implicit linear systems including admissibility analysis, impulse elimination, feedback control, normalization, and so on.

On the other hand, in recent years, a great number of attention has been paid to Markovian jump systems (MJSs) because of MJSs representing many practical systems with sudden diversifications in parameters or structure [18]–[30]. When implicit systems meet with sudden diversifications in their structure/parameters, the implicit MJSs (IMJSs) come into being. Many works about IMJSs have been reported in recent years, for instance, [6], [31]–[40] and the references therein.

It should be pointed out that literature [6] evidently demonstrated the necessary-sufficient admissibility conditions for IMJSs in terms of strict LMIs, the slow-fast (S-F) decomposition and singular value decomposition techniques mentioned in [1] were employed. From then on, Xia *et al.* [34] considered admissibility and stabilization for continuous-time IMJSs; [35] was concerned with admissibility for Itô stochastic IMJSs based on matrix decomposition technique, while [35] did not consider the problems of controller design and

Command Filter-Based Adaptive Prescribed Performance Tracking Control for Stochastic Uncertain Nonlinear Systems

Wei Sun, *Member, IEEE*, Shun-Feng Su, *Fellow, IEEE*, Jianwei Xia, and Guangming Zhuang

***Abstract*—The issue of adaptive fuzzy prescribed performance tracking control is considered in this article for strict-feedback stochastic uncertain nonlinear systems. A novel adaptive tracking control design approach, in which the fuzzy systems are employed to approximate the totally unknown nonlinear terms, is proposed by incorporating the technology of prescribed performance control with the method of command filtered backstepping design. The proposed adaptive state feedback controller can ensure that the output tracking error converges to a predefined arbitrarily small residual set in probability and all the signals of the closed-loop system can be bounded in probability, meanwhile, the problem of "explosion of complexity" is solved. The effectiveness of the presented method is verified by two simulation examples.**

***Index Terms*—Adaptive tracking control, command filter backstepping design, fuzzy control, prescribed performance.**

I. Introduction

IN THE past 20 years, backstepping design has become a powerful tool for the control design of nonlinear systems, especially for the strict-feedback nonlinear systems, and a lot of research results are acquired (see [1]–[4]). The emergence of adaptive technology makes the backstepping design successfully solve the control problems of many uncertain strict-feedback nonlinear systems. It is needed to point out that the uncertain terms can be linearly parameterized or have previous information of the bound in the early research. However, these assumptions may not be supported for some systems. Due to the good learning ability, fuzzy systems [5]–[9] or neural networks [10]–[13] are frequently used to solve the adaptive control design of uncertain systems with structural uncertainty or completely unknown nonlinear function. In particular, in view of fuzzy control, the issue of synchronization control of complex dynamical networks with nonlinear couplings and uncertainties is solved in [14]. An adaptive decentralized fault-tolerant tracking control scheme is proposed in [15] for interconnected nonlinear systems. As a practical application, an optimal fuzzy controller is designed in [16] for a ball and beam system. Since most of the practical mechanical systems are frequently affected by stochastic disturbances, for instance, robotics working in a marine environment, dynamic system of the aircraft. Many researchers have threw themselves to the study of stochastic nonlinear systems. Meantime, backstepping design technique has been successfully applied to stochastic cases [17]–[19].

All the researchers have to face the tough problem when they use the backstepping method, i.e., the repeating derivations of virtual controllers for all the states in the last subsystem appear, which is termed as "explosion of complexity." Fortunately, a command filtered technology is developed in [20] and [21] to alleviate this problem. From that moment on, the command filtered backstepping design is applied to the control for a variety of nonlinear systems. By using command filtering design, the issue of adaptive fuzzy control is solved in [22] for uncertain nonlinear systems under the case of dead-zone input. In [23] and [24], command filtering design is further, respectively, applied to practical stochastic induction motors nonlinear systems and MIMO uncertain nonlinear systems with input saturation. An adaptive tracking controller via a neural networks approach is constructed in [25] for a class of switched and output constrained nonlinear systems. Via an adaptive fault-tolerant control and command filtering design, the finite-time control methods are developed in [26] and [27] for strict-feedback nonlinear systems. Moreover, the issue of tracking control by fuzzy control and command filtering design is discussed in [28] for a class of MIMO uncertain switched nonstrict feedback nonlinear systems, and so on.

In recent years, prescribed performance control of nonlinear systems received much attention in the control field, since some requirements of performance behavior arise in many control engineering, such as convergence rate, overshoot, and maximum steady-state error. In [29], the concept of performance function is proposed and a robust adaptive prescribed performance control is

Manuscript received December 8, 2019; accepted December 26, 2019. This work was supported in part by the National Natural Science Foundation of China under Grant 61603170, Grant 61973148, and Grant 61773191, in part by the Minister of Science and Technology, Taiwan, under Grant MOST 108-2221-E-011-159, in part by the "Center for Cyber-Physical System Innovation" from the Featured Areas Research Center Program within the framework of the Higher Education Sprout Project by the Ministry of Education in Taiwan, and in part by the Support Plan for Outstanding Youth Innovation Team in Shandong Higher Education Institutions under Grant 2019KJI010. This article was recommended by Associate Editor J. Sarangapani. *(Corresponding author: Shun-Feng Su.)*

Wei Sun, Jianwei Xia, and Guangming Zhuang are with the School of Mathematics Science, Liaocheng University, Liaocheng 252000, China (e-mail: sunw8617@163.com; njustxjw@126.com; zgmtsg@126.com).

Shun-Feng Su is with the Department of Electrical Engineering, National Taiwan University of Science and Technology, Taipei 106, Taiwan (e-mail: sfsu@mail.ntust.edu.tw).

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSMC.2019.2963220

Adaptive Intelligent Control for Input and Output Constrained High-Order Uncertain Nonlinear Systems

Wei Sun, Shun-Feng Su, *Fellow, IEEE*, Zhen-Guo Liu, and Zong-Yao Sun

***Abstract*—This article reports this article on the problem of adaptive fuzzy output tracking control for a category of high-order nonlinear systems with input saturation, output constraint, and serious uncertainties. A high-order barrier Lyapunov function and an auxiliary Hyperbolic Tangent function is employed to deal with output constraint and input saturation, respectively. By incorporating a backstepping design technique, adaptive fuzzy control, and adding a power integrator, a novel control scheme is designed to ensure that all states in the resulting closed-loop system are bounded and the tracking error converges to a bounded compact set. Moreover, two simulations are conducted to verify the effectiveness of the design method.**

***Index Terms*—Adaptive fuzzy tracking control, high-order nonlinear system, input saturation, output constraint.**

I. Introduction

THE PROBLEM of control design for uncertain nonlinear systems has become a hot topic [1]–[4] over the past two decades. Although considerable efforts have been made to achieve various excellent control objectives for the related control systems, it is still a challenging issue because multifarious kinds uncertainties exist in systems, such as parameters variations, external disturbance, unmodeled dynamics, etc. Generally speaking, the usual adaptive control methods can be used to resolve the parametric uncertainties problem. However, nonparametric uncertainties exist in most systems, in this case, the traditional adaptive control approaches may result in unsatisfactory control performance. Adaptive fuzzy control or neural networks control are proposed, respectively, to resolve this problem [5]–[11]. Especially, the backstepping technique has been successfully applied to adaptive fuzzy control of strict-feedback nonlinear systems [12]–[14].

The traditional backstepping design is not applicable to high-order nonlinear system, which is a more general form of strict-feedback nonlinear systems. A method of adding a power integrator is built in [15] to solve stabilization and tracking control problems for such more general systems. Lots of results have been acquired in view of such an approach as yet, such as two different adaptive control schemes are addressed in [16] for high-order nonlinear systems with time-delay. An improved finite-time control method is designed in [17]. Moreover, the problem of finite-time stabilization is extended to stochastic higher order nonlinear systems in [18] and [19]. For more complex multiple stochastic high-order nonlinear systems, the problem of distributed cooperative control is discussed in [20]. In view of neural networks control, an adaptive tracking controller under arbitrary deterministic switching is considered in [21] for high-order stochastic switched nonlinear systems, and so on.

Control design for real applications is frequently involved with several restrictions. One of these is the output constraint. Barrier Lyapunov function has turn into a primary tool to carry on the control design and to analyze constrained nonlinear systems in recent years, such as strict feedback systems [22], [23], nonstrict feedback systems [24], [25], and MIMO nonlinear systems [26]–[28]. Besides, the stabilization and tracking control problems are solved in [29]–[33] for full-state constrained nonlinear systems. On the other hand, saturation characteristics are common in many actual control systems. Ignoring this important nature in control design may degrade the control performance or even completely destroy the stability of system. Hence, research on this issue has never stopped, such as the adaptive tracking control algorithm in [34] for a class of input constrained MIMO nonlinear systems. For a family of time-varying full-state constrained uncertain nonlinear systems with input saturation, the problem of tracking control is solved in [35]. Two control strategies are proposed in [36] for single input uncertain nonlinear systems under both input saturation and external disturbances. For input constrained multiagent systems, an effective control scheme

Manuscript received April 16, 2019; revised July 22, 2019 and September 26, 2019; accepted November 23, 2019. Date of publication December 6, 2019; date of current version August 18, 2021. This work was supported in part by the National Natural Science Foundation of China under Grant 61603170, Grant 61773237, and Grant 61603231, in part by the Minister of Science and Technology, Taiwan, under Grant MOST 108-2221-E-011-159, and in part by the "Center for Cyber-Physical System Innovation" from the Featured Areas Research Center Program Within the Framework of the Higher Education Sprout Project by the Ministry of Education in Taiwan. This article was recommended by Associate Editor Y. Zhao. *(Corresponding author: Shun-Feng Su.)*

W. Sun is with the School of Mathematics Science, Liaocheng University, Liaocheng 252000, China, and also with the Center for Cyber-Physical System Innovation, National Taiwan University of Science and Technology, Taipei 106, Taiwan (e-mail: sunw8617@163.com).

S.-F. Su is with the Department of Electrical Engineering, National Taiwan University of Science and Technology, Taipei 106, Taiwan (e-mail: sfsu@mail.ntust.edu.tw).

Z.-G. Liu is with the Department of Automation, Shanxi University, Taiyuan 030006, China (e-mail: lzg819@163.com).

Z.-Y. Sun is with the Institute of Automation, Qufu Normal University, Qufu 273165, China (e-mail: sunzongyao@sohu.com).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TSMC.2019.2956063.

Digital Object Identifier 10.1109/TSMC.2019.2956063

Fixed-Time Adaptive Neural Network Control for Nonlinear Systems With Input Saturation

Wei Sun, *Senior Member, IEEE*, Shuzhen Diao, Shun-Feng Su, *Fellow, IEEE*, and Zong-Yao Sun

***Abstract*—This study concentrates on the tracking control problem for nonlinear systems subject to actuator saturation. To improve the performance of the controller, we propose a fixed-time tracking control scheme, in which the upper bound of the convergence time is independent of the initial conditions. In the control scheme, first, a smooth nonlinear function is employed to approximate the saturation function so that the controller can be designed under the framework of backstepping. Then, the effect of input saturation is compensated by introducing an auxiliary system. Furthermore, a fixed-time adaptive neural network control method is given with the help of fixed-time control theory, in which the dynamic order of controllers is reduced to a certain extent since there is only one updating law in the entire control design. Through rigorous theoretical analysis, it is concluded that the proposed control scheme can guarantee that: 1) the output tracking error can converge to a small neighborhood near the origin in a fixed time and 2) all signals in the closed-loop system are bounded. Finally, a numerical example and a practical example based on the single-link manipulator are provided to verify the effectiveness of the proposed method.**

***Index Terms*—Adaptive tracking control, fixed-time control, input saturation, neural network (NN).**

I. Introduction

IN RECENT decades, because of the universality of nonlinear systems in the real world, scholars have gradually deepened the research on various nonlinear systems, such as high-order systems [1], switched systems [2], and multiagent systems [3]. With the development of intelligent control methods such as fuzzy logic systems (FLSs) and neural networks (NNs), a large number of valuable control methods have been proposed to perfect the theory of nonlinear systems from different perspectives and to provide ideas for resolving the difficulties in engineering applications [4]–[9]. For example, based on a neural adaptive output-feedback control method, the problem of generalized function projective synchronization for nonlinear fractional-order chaotic systems is discussed in [4]. For the lower limb exoskeleton system and the underactuated system with state constraints, two adaptive control algorithms are given in [5] and [6] to resolve the tracking control problem. In addition to actual mechanical systems, adaptive NN control is also extended to the problem of cancer treatment in [7]. On the other hand, as production equipment and processes become more and more complex, it is very difficult to construct an accurate system model. Compared with model-based control, data-driven control adopted in [8] and [9] can directly design controllers by using a large amount of offline/online data and knowledge, and those approaches can improve the robustness of the control system and effectively deal with the control problems of controlled objects that are difficult to model. Moreover, NNs are often used for data-driven control since detailed information about system dynamics is not required. Especially with the development of data storage technology, the control problem based on data-driven design and NNs has made great progress. With the aid of iterative learning control and NNs, two iterative data-driven control algorithms that can achieve optimal control are given in [8] and [9]. The latter can be used in the wastewater treatment process and has important practical significance. As we all know, the nonlinearity in the actual system may be in the system itself or it may be the nonlinear characteristic in the system components. Hence, many experts and scholars also devote themselves to the research on these nonlinear characteristics, such as hysteresis, dead zone, and input saturation, and constantly put forward new control methods and ideas [10]–[13].

Out of considerations such as safety requirements and physical limitations, most practical systems are usually constrained by many practical conditions, i.e., various input constraints, output constraints, or state constraints [14]–[19]. At present, under the framework of backstepping control design, many scholars usually employ the barrier Lyapunov function to study control problems related to nonlinear systems subject to state or output constraints [17]–[19]. On the other hand, the input saturation nonlinearity is also a typical input constraint. Compared to other nonlinear characteristics, actuator saturation is most likely to occur in the actual system operation process. If there is the saturation characteristic in the actuator, when the actuator input reaches the limit value, the increase of the actuator input will no longer affect the output. In other words, the actuator output will be infinitely close to or equal to a fixed value at this time. This is equivalent to weakening the original control power of the input signal. Due to this situation,

Manuscript received March 12, 2021; revised June 29, 2021; accepted August 14, 2021. This work was supported by the Natural Science Foundation of Shandong Province for Key Projects under Grant ZR2020KA010. *(Corresponding author: Shun-Feng Su.)*

Wei Sun and Shuzhen Diao are with the School of Mathematical Science, Liaocheng University, Liaocheng 252000, China (e-mail: sunw8617@163.com; diaoshuzhen@163.com).

Shun-Feng Su is with the Department of Electrical Engineering, National Taiwan University of Science and Technology, Taipei 106, Taiwan (e-mail: sfsu@mail.ntust.edu.tw).

Zong-Yao Sun is with the Institute of Automation, Qufu Normal University, Qufu 273165, China (e-mail: sunzongyao@sohu.com).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TNNLS.2021.3105664.

Digital Object Identifier 10.1109/TNNLS.2021.3105664