A Contraction Theory-Based Adaptive Robust Control for the Trajectory Tracking of a Pneumatic Cylinder

Ye Chen, Guoliang Tao, and Xiang Fan

***Abstract*—Adaptive robust control (ARC) has been applied to pneumatic systems successfully for its excellent performance and strong robustness. Although many researchers are already working on studying of the ARC, the stability analyses of these works are performed by the Lyapunov method. The contraction theory is a new proposed "differential" Lyapunov-like analytic tool for the nonautonomous nonlinear system. It can provide a more convenient analysis and richer design toolbox of the nonlinear system than Lyapunov method. This article intelligently brings the philosophy of contraction theory into the ARC design framework to form a contraction theory-based ARC (CT-ARC) for a pneumatic servo system. The proposed method offers more design choices than the traditional ARC. In addition, a command filter is employed to acquire the differential signal of the virtual control law. The stability analysis of the whole system is presented elegantly by the contraction theorem with consideration of the estimation error of the command filter. Furthermore, exponential convergence of the closed-loop system can be derived under specific conditions. Finally, various experiments for the trajectory tracking control of a pneumatic cylinder demonstrate the efficiency of CT-ARC.**

***Index Terms*—Adaptive robust control (ARC), command filter, contraction theory, pneumatic servo system.**

I. Introduction

RECENTLY, pneumatic servo systems have been widely applied in industry for the strengths: low-cost, cleanliness, safety, speed, high-power-weight ratio, and ease of maintenance [1], [2], [3], [4]. The pneumatic cylinder is a commonly used actuator for achieving linear or rotation motion [5]. However, the high intrinsic nonlinearity of the pneumatic cylinder system, which contains the compressibility of air, variable friction, and random disturbances, makes high-performance control of the servo system a challenging task [6], [7], [8]. The state-of-the-art control algorithms should be applied to pneumatic systems to broaden the applications to more high-end markets.

Manuscript received 17 April 2023; revised 24 September 2023; accepted 8 November 2023. Date of publication 28 November 2023; date of current version 5 June 2024. *(Corresponding author: Ye Chen.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TIE.2023.3332993.

Digital Object Identifier 10.1109/TIE.2023.3332993

The history of pneumatic servo control can be traced back to the 1950s [9]. In the beginning, the proportional, integral and derivative (PID) controllers have been applied to the pneumatic servo system for the advantages of simplicity and easy to implement. But it is tough for pneumatic systems to achieve the desired performance globally with linear controllers due to the strong nonlinearities of pneumatic systems [10]. Many different types of nonlinear controllers have been developed to improve the performance. The most studied are the deterministic robust control (DRC) [11], [12] and adaptive control (AC) [13], [14]. These two methods deal with two different types of model uncertainties: uncertain nonlinearities and parametric certainties. DRC is famous for its robustness and capability to attenuate disturbances. AC is an effective way to estimate unknown parameters. An adaptive robust controller (ARC) that simultaneously handles these two types of model uncertainties has been designed for pneumatic systems successfully [6], [15], [16]. ARC controller, which achieves a precise tracking control as AC, while robustness to unknown disturbances as DRC, is an effective way to solve the performance tracking control of pneumatic servo systems.

Recently, a contraction theory technique has been applied to the nonlinear control design [17], [18], [19], [20]. Control algorithms with robustness and learning capability (e.g., robust feedback control, AC) have been developed based on contraction theory [21], [22], [23], [24], [25]. Generally, contraction theory has advantages for the analysis of nonlinear nonautonomous systems [24]. Hence, it is very attractive to develop a contraction theory-based ARC (CT-ARC) for the trajectory tracking of nonlinear systems like pneumatic servo systems. On the other hand, all the results of contraction theory-based control in the literature remain theoretical and are only verified by simulations. No practical experiments have been carried out so far. It is necessary to testify the effectiveness of the novel design tool with real experiments. Pneumatic servo systems with strong nonlinearities are suitable experiment objects to confirm the efficacy of contraction theory-based control algorithms.

Motivated by the observations above, this article proposed a CT-ARC for pneumatic servo systems. The main contribution is summarized as follows.

1) A novel ARC based on contraction theory is designed for pneumatic servo systems. Both guaranteed transient performance and exponential convergence of CT-ARC

Original Paper

MEASUREMENT AND CONTROL

Measurement and Control
1–13

DOI: 10.1177/00202940231200956
journals.sagepub.com/home/mac
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A dual adaptive robust control for nonlinear systems with parameter and state estimation

Ye Chen, Guoliang Tao and Yitao Yao

Abstract

Stabilization and learning are imperative to the high-performance feedback control of nonlinear systems. A dual adaptive robust control (DARC) scheme is proposed for nonlinear systems with model uncertainties to achieve a desired level of performance. Only the output of the nonlinear system is accessible in this work, all the states and parameters are learned online. Firstly, the DARC uses the prior physical bounds of systems to design a discontinuous projection with update rate limits which confines the bounds of parameter and state estimation. Then robustness of the nonlinear system can be guaranteed by the deterministic robust control (DRC) method. Secondly, a dual adaptive estimation mechanism (DAEM) is developed to learn the unknown parameters and states of systems. One part of the DAEM is the bounded gain forgetting (BGF) estimator, which is developed to handle inaccurate parameters and parametric variations. The other is the adaptive unscented Kalman filter (AUKF) synthesized for state estimation. The AUKF contains a statistic estimator based on the maximum a posterior (MAP) rule to estimate the unknown covariance matrix. Finally, simulation results illustrate the effectiveness of the suggested method.

Keywords

Adaptive control, adaptive unscented Kalman filter, nonlinear systems, system identification

Date received: 18 August 2022; accepted: 26 August 2023

Introduction

Performant feedback control of nonlinear systems is impeded by inaccurate dynamical models. To improve the performance of nonlinear systems, the estimation of parameters and states are heavily studied by researchers.[1–4] Adaptive control is a well-known technique for the online estimation of parameters.[5–8] Also, many approaches have been developed for the state estimation of nonlinear systems, especially the nonlinear Kalman filter.[9–11] However, simultaneous estimating the parameters and states of nonlinear systems is still a challenging problem. The conventional approach, such as extended Kalman filter (EKF) and extended Luenberger observer, is simply linearizing the nonlinear model and building an augmented state system with parameters such that the traditional linear method can be applied to the estimation of the augmented states.[12–14] Nevertheless, these methods suffer from the drawbacks of heavy computation of the Jacobi matrix and limited precision of the first order.[15,16] With higher accuracy, the unscented Kalman filter (UKF) is implemented for parameter and state estimation of nonlinear systems.[17,18] Both the joint UKF and dual UKF methods are under the framework of Kalman, which needs exact knowledge of prior statistics. In practice, statistics are hard to know and often inaccurate. Thus the performance of estimation might be degraded or even diverge.[19] To avoid performance degradation, many different types of adaptive unscented Kalman filter (AUKF) with statistic estimator are applied to industrial areas.[20,21] Though the adaptive mechanism of AUKF is effective, this method assumes that parameters are constants disturbed by small Gaussian noises which are usually not satisfied. The AUKF with Gaussian distribution assumptions also has a limited tracking capability of parameters, but the actual operating environment for nonlinear systems is complex and parameters are usually time-varying. This work integrates the bounded gain forgetting (BGF) estimator[1] and AUKF to form a dual adaptive estimation mechanism (DAEM). The bounded gain forgetting (BGF) estimator with parameter tracking ability while avoiding adaptation

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Control Engineering Practice 137 (2023) 105556

Contents lists available at ScienceDirect

Control Engineering Practice

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

A composite adaptive robust control for pneumatic servo systems with time-varying inertia

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ARTICLE INFO

MSC:
00-01
99-00

Keywords:
Pneumatic servo systems
Adaptive robust control
Composite adaptive control

ABSTRACT

This article proposes a composite adaptive robust control for a pneumatic servo system with time-varying inertia to achieve a good tracking performance. The proposed design not only preserves the merits of both direct adaptive robust control and indirect adaptive robust control but also obtains a better performance of the working condition with time-varying inertias. Firstly, prescribed tracking performance is guaranteed without knowing the bounds of parametric and non-parametric uncertainties by leveraging a discontinuous projection and deterministic robust control technique. And a nonlinear tracking differentiator is used to obviate differential signal in backstepping. Secondly, the online parametric estimation algorithm is developed by intelligently integrating tracking error dynamics and physical plant dynamics. By effectively using the information of both tracking error and prediction error, a high adaptation gain can be used for achieving a faster parameter convergence and smaller tracking error. Moreover, exponential convergence of both tracking error and prediction error can be obtained under certain conditions. Lastly, comparative experiments on different conditions are carried out for a single-rod pneumatic cylinder driven by a proportional directional valve to demonstrate the superiority of the proposed method.

1. Introduction

Pneumatic servo systems are widely applied in industrial automation (Dong, Shi, Liu, & Yu, 2021; Inoue, Kanno, Miyazaki, Kawase, & Kawashima, 2020; Liu, Wang, Zhao, & Ma, 2022; Pipan & Herakovic, 2018; Zhao, Sun, Yang, & Wang, 2019; Zhao, Xia, Yang, & Zhang, 2022). Compared to hydraulic and electric motor systems, it owns advantages of economics, simple in structure, long working life, easy to maintain, and environment-friendly. Recently, due to the cheap computation of the microprocessor, many advanced control algorithms have been designed for pneumatic servo systems (Herzig, Moreau, Redarce, Abry, & Brun, 2018; Mu, Goto, Shibata, & Yamamoto, 2019; Ren, Jiao, Li, & Deng, 2022; Ren, Wang, Fan, & Kaynak, 2019). And the applications of pneumatic systems are extended from low-end products to more complex working areas, such as robotics and medical instruments (Dong, Zhang, & Liu, 2018; Li, Yuan, Wang, & Guo, 2022; Zhang et al., 2022). On one hand, these novel applications demand better performance but face more complex working conditions that are often time-varying. On the other hand, pneumatic systems have strong intrinsic nonlinearities, including gas compressibility, the nonlinear flow through the valve port, complex friction, random disturbances, etc. It is urgent to improve the tracking performance of pneumatic servo systems, which is a challenging task.

In the early stage, traditional proportional–integral–derivative (PID) control for the pneumatic system is developed for the merits of simplicity and high-reliability (Shearer, 1956; Van Varseveld & Bone, 1997). However, the PID controllers mainly consider the point-to-point positioning control problem. To improve the performance of the pneumatic servo system, many modified PID control strategies have been proposed (Mu et al., 2019; Ren, Fan, & Kaynak, 2018; Tian, Yan, & Zhang, 2019). These methods are effective for a specific working condition but vulnerable to variations in the system and operational environment. In general, linear modified techniques can achieve high performance of the system near the linearization point. The strong nonlinear dynamics of the pneumatic systems determine that these techniques cannot meet the control target of more complex working conditions, such as different reference trajectories, various payloads, and unknown external disturbances. To handle more complex operation conditions, model-based methods for pneumatic servo systems are studied by researchers heavily. The sliding mode controller is designed for pneumatic systems for its strong robust ability to attenuate unknown nonlinearities (Azahar, Irawan, & Ismail, 2021; Tran et al., 2020; Wang, Wang, & Wang, 2019). Although the stability of pneumatic servo systems is ensured by the sliding mode controller, the state-steady performance is not good enough for inaccurate model compensation. By contrast, adaptive control is famous for its online learning with

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https://doi.org/10.1016/j.conengprac.2023.105556
Received 1 October 2022; Received in revised form 21 March 2023; Accepted 26 April 2023
Available online xxxx

Received: 2 March 2022 | Revised: 25 December 2022 | Accepted: 6 March 2023

DOI: 10.1002/rnc.6669

RESEARCH ARTICLE

WILEY

A composite adaptive robust control for nonlinear systems with model uncertainties

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Abstract

This article is concerned with a composite adaptive robust control (CARC) for non-strict feedback nonlinear systems with model uncertainties including parametric uncertainties and uncertain nonlinearities. It is assumed that the model uncertainties of the nonlinear system are bounded but unknown. Firstly, prescribed tracking performance is achieved by the CARC control law even the unknown parameters are time-varying. This is accomplished firstly by designing a discontinuous projection that confines the unknown parameters in an estimated region. Then the robustness of the closed-loop system is guaranteed by leveraging the deterministic robust control philosophy. Also, a command filter has been designed to avoid computing complex derivatives of virtual control law in the backstepping procedure. Secondly, a composite adaptation law that intelligently integrates information of both tracking error and prediction error is constructed for improving the performance of controllers. The high adaptation gain of CARC leads to higher parameter convergence speed and smaller tracking errors. Moreover, if the actual parameters are within the design range, asymptotic stability can be achieved in presence of parametric uncertainties only. In addition, exponential convergence of tracking errors and parameters can be shown under certain conditions. Finally, numerical examples are made to validate the superiority and effectiveness of the proposed control scheme.

KEYWORDS

adaptive robust control, composite adaptive control, nonlinear systems

1 | INTRODUCTION

An accurate dynamical model of nonlinear systems is necessary for high-performance feedback control. However, an accurate dynamical model is very hard to acquire. The real operation environment is complex, and many uncertainties exist in nonlinear systems. Generally, the primary concern for model uncertainties of nonlinear systems is the parametric uncertainties and uncertain nonlinearities.[1] Parametric uncertainties are about the known nonlinear features of a system with unknown parameters. The unknown nonlinear features, disturbances, and modeling errors are referred to as uncertain nonlinearities.

An adaptive robust control (ARC),[2-4] which intelligently integrates adaptive control[5-7] and deterministic robust control,[8-10] has been studied heavily for its capability to handle parametric uncertainties and uncertain nonlinearities simultaneously. Being robust to model uncertainties while retaining the ability of model learning, the ARC control

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High Precision Adaptive Robust Neural Network Control of a Servo Pneumatic System

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Received: 13 July 2019; Accepted: 20 August 2019; Published: 22 August 2019

Abstract: In this paper, an adaptive robust neural network controller (ARNNC) is synthesized for a single-rod pneumatic actuator to achieve high tracking accuracy without knowing the bounds of the parameters and disturbances. The ARNNC control framework integrates adaptive control, robust control, and neural network control intelligently. Adaptive control improves the precision of dynamic compensation with parametric estimation, and robust control attenuates the effect of unmodeled dynamics and unknown disturbances. In reality, the unmodeled dynamics of the complicated pneumatic systems and unpredictable disturbances in working conditions affect the tracking precision. However, these cannot be expressed as an exact formula. Therefore, the real-time learning radial basis function (RBF) neural network component is considered for better compensation of unmodeled dynamics, random disturbances, and estimation errors of the adaptive control. Although the bounds of the parameters and disturbances for the pneumatic systems are unknown, the prescribed transient performance and final tracking accuracy of the proposed method can be still achieved with fictitious bounds. Asymptotic tracking performance can be acquired under the provided circumstance. The comparative experiments with a pneumatic cylinder driven by proportional direction valve illustrate the effectiveness of the proposed ARNNC as shown by a high tracking accuracy is achieved.

Keywords: adaptive robust control; neural network; pneumatic systems

1. Introduction

Pneumatic actuators have been widely used in industrial applications due to the advantages of having a high power/mass ratio, being low cost, clean, and easily serviced [1–3]. Some examples are pneumatic force actuator systems [1,4], positioning control systems [5], and rehabilitation devices [6]. However, the dynamics of the pneumatic system are complicated, including the nonlinearities of pressure dynamics, the compressibility of air, unmodeled friction, and random disturbances, etc. The unmodeled dynamics, disturbances, and inaccurate mathematic models result in achieving precise motion control of pneumatic cylinders being a challenging task.

The linear control strategy and modified linear control techniques [5,7,8] are widely applied to the pneumatic systems, but the strong nonlinear dynamics of pneumatic systems restrict the capability of a linear controller in achieving a high precision tracking performance. Therefore, the model-based control strategy is considered for pneumatic systems [9]. The sliding mode control [10–12] method is introduced to pneumatic systems for strong robustness; however, it has limited capacity to compensate for nonlinear dynamics. In addition, the backstepping [13] technique is used for controller design and stability analysis of the pneumatic systems. The adaptive control strategy [14] is used for pneumatic systems to obtain a more precise model compensation but is vulnerable to disturbances. Adaptive robust control (ARC) [15,16] takes advantages of robust control and adaptive control to acquire robustness and better tracking performance. Zhu et al. [17,18] devised the adaptive robust controller for a parallel manipulator driven by pneumatic muscles, and significant performance was

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第 1 条，共 1 条
标题:A Contraction Theory-Based Adaptive Robust Control for the Trajectory Tracking of a Pneumatic Cylinder
作者: Chen, Y(Chen, Ye);Tao, GL(Tao, Guoliang);Fan, X(Fan, Xiang);
来源出版物:IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS **提前访问日期:**NOV 2023
DOI:10.1109/TIE.2023.3332993 **出版年:**2023 NOV 28 2023
入藏号:WOS:001112835600001
文献类型: Article; Early Access
地址:
[Chen, Ye; Tao, Guoliang; Fan, Xiang] Zhejiang Univ, State Key Lab Fluid Power & Mechatron Syst, Hangzhou 310058, Peoples R China.
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电子邮件地址:11625056@zju.edu.cn; gltao@zju.edu.cn; fx@zju.edu.cn
IDS 号:Z5YV0
ISSN:0278-0046
eISSN:1557-9948

期刊《IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS》2022年的影响因子为7.7，五年影响因子为8.6。
期刊《IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS》2023年升级版的中科院期刊分区情况为：

刊名	IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS		
年份	2023		
ISSN	0278-0046		
	学科	分区	Top 期刊
大类	工程技术	1	是
小类	AUTOMATION & CONTROL SYSTEMS 自动化与控制系统	1	-
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第 1 条，共 5 条
标题:A Contraction Theory-Based Adaptive Robust Control for the Trajectory Tracking of a Pneumatic Cylinder
作者:Chen, Y(Chen, Ye);Tao, GL(Tao, Guoliang);Fan, X(Fan, Xiang);
来源出版物:IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS **提前访问日期:**NOV 2023
DOI:10.1109/TIE.2023.3332993 **出版年:**2023 NOV 28 2023
入藏号:WOS:001112835600001
文献类型:Article; Early Access
地址:
[Chen, Ye; Tao, Guoliang; Fan, Xiang] Zhejiang Univ, State Key Lab Fluid Power & Mechatron Syst, Hangzhou 310058, Peoples R China.
通讯作者地址:
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电子邮件地址:11625056@zju.edu.cn; gltao@zju.edu.cn; fx@zju.edu.cn
IDS 号:Z5YV0
ISSN:0278-0046
eISSN:1557-9948

第 2 条，共 5 条
标题:A composite adaptive robust control for pneumatic servo systems with time-varying inertia
作者:Chen, Y(Chen, Ye);Tao, GL(Tao, Guoliang);Yao, YT(Yao, Yitao);
来源出版物:CONTROL ENGINEERING PRACTICE **卷:**137 **文献号:**105556 **提前访问日期:**MAY 2023
DOI:10.1016/j.conengprac.2023.105556 **出版年:**AUG 2023
入藏号:WOS:001006959300001
文献类型:Article
地址:
[Chen, Ye; Tao, Guoliang; Yao, Yitao] Zhejiang Univ, Dept Mechatron Engn, State Key Lab Fluid Power & Mechatron Syst, Hangzhou, Peoples R China.
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电子邮件地址:11625056@zju.edu.cn
IDS 号:J0YW8
ISSN:0967-0661
eISSN:1873-6939

第 3 条，共 5 条
标题:A composite adaptive robust control for nonlinear systems with model uncertainties
作者:Chen, Y(Chen, Ye);Tao, GL(Tao, Guoliang);Yao, YT(Yao, Yitao);
来源出版物:INTERNATIONAL JOURNAL OF ROBUST AND NONLINEAR CONTROL **卷:**33 **期:**10 **页:**5800-5818
提前访问日期:MAR 2023 **DOI:**10.1002/rnc.6669 **出版年:**JUL 10 2023
入藏号:WOS:000954547700001
文献类型:Article
地址:
[Chen, Ye; Tao, Guoliang; Yao, Yitao] Zhejiang Univ, State Key Lab Fluid Power & Mechatron Syst, Hangzhou, Peoples R China.
通讯作者地址:
Tao, GL (corresponding author), Zhejiang Univ, State Key Lab Fluid Power & Mechatron Syst, Hangzhou, Peoples R China.
电子邮件地址:gltao@zju.edu.cn

IDS 号:H8TE7
ISSN:1049-8923
eISSN:1099-1239

第 4 条，共 5 条
标题:A dual adaptive robust control for nonlinear systems with parameter and state estimation
作者:Chen, Y(Chen, Ye);Tao, GL(Tao, Guoliang);Yao, YT(Yao, Yitao);
来源出版物:MEASUREMENT & CONTROL **卷:**57 **期:**4 **页:**378-390 **提前访问日期:**OCT 2023
DOI:10.1177/00202940231200956 **出版年:**APR 2024
入藏号:WOS:001081750200001
文献类型: Article
地址:
[Chen, Ye; Tao, Guoliang; Yao, Yitao] Zhejiang Univ, State Key Lab Fluid Power & Mechatron Syst, Hangzhou, Zhejiang, Peoples R China.
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电子邮件地址:11625056@zju.edu.cn
IDS 号:KY5H1
ISSN:0020-2940
eISSN:2051-8730

第 5 条，共 5 条
标题:High Precision Adaptive Robust Neural Network Control of a Servo Pneumatic System
作者:Chen, Y(Chen, Ye);Tao, GL(Tao, Guoliang);Liu, H(Liu, Hao);
来源出版物:APPLIED SCIENCES-BASEL **卷:**9 **期:**17 **文献号:**3472 **DOI:**10.3390/app9173472 **出版年:**SEP 1 2019
入藏号:WOS:000488603600034
文献类型: Article
地址:
[Chen, Ye; Tao, Guoliang; Liu, Hao] Zhejiang Univ, State Key Lab Fluid Power & Mechatron Syst, Hangzhou 310027, Zhejiang, Peoples R China.
通讯作者地址:
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电子邮件地址:gltao@zju.edu.cn
IDS 号:JB5LE
eISSN:2076-3417

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2024 年 3 月 28 日