ISA Transactions xxx (2018) 1–10

Contents lists available at ScienceDirect

ISA Transactions

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

Practice article

Design of an adaptive super-twisting decoupled terminal sliding mode control scheme for a class of fourth-order systems

Donya Ashtiani Haghighi, Saleh Mobayen*

Electrical Engineering Department, University of Zanjan, Zanjan, Iran

A R T I C L E I N F O

Article history:
Received 7 October 2017
Received in revised form
14 January 2018
Accepted 5 February 2018
Available online xxx

Keywords:
Terminal sliding mode control
Decoupled sliding mode control
Adaptive tuning
Cart-pole system
Unknown uncertainties

A B S T R A C T

This paper proposes an adaptive super-twisting decoupled terminal sliding mode control technique for a class of fourth-order systems. The adaptive-tuning law eliminates the requirement of the knowledge about the upper bounds of external perturbations. Using the proposed control procedure, the state variables of cart-pole system are converged to decoupled terminal sliding surfaces and their equilibrium points in the finite time. Moreover, via the super-twisting algorithm, the chattering phenomenon is avoided without affecting the control performance. The numerical results demonstrate the high stabilization accuracy and lower performance indices values of the suggested method over the other ones. The simulation results on the cart-pole system as well as experimental validations demonstrate that the proposed control technique exhibits a reasonable performance in comparison with the other methods.

1. Introduction

1.1. Background and motivation

In the past decades, the sliding mode control (SMC) technique has been extensively applied to the stabilization of various linear and nonlinear systems [1,2]. Its main advantages contain the robustness in contrast to parameter variations and external disturbances, guaranteed stability, fast response and easiness in employment. In general, the design process of SMC consists of two steps: (a) design of a suitable sliding surface; (b) design of a control law. The first step includes the selection of an appropriate switching surface such that makes the states of the system to stay along with it [3,4]. The second step concerns with the design of a suitable controller, which forces states of the system to reach the sliding surface [5,6]. When states of the system reach the sliding surface, the order of the control system is reduced and then, the system can dominate the certain external disturbances and matched uncertainties [7,8]. Nevertheless, the conventional SMC has some important weaknesses that the robustness of the control system is not satisfied in the reaching phase and there exists high-frequency oscillations (chattering) in the control signal which is undesirable [9].

In order to realize finite-time convergence of the states, a new scheme of SMC method called terminal sliding mode control (TSMC) has been developed [10]. TSMC proposes some superior features such as high tracking accuracy, fast and finite-time convergence [11–13]. Although TSMC has been extensively employed to design the controller for linear and nonlinear systems [14,15], it TSMC suffers from the singularity phenomenon which produces an unbounded control input owing to the negative fractional power existed in the nonlinear sliding surface [16,17]. In TSMC, a nonlinear term is added to the sliding surface to improve the system's convergence [18,19]. This technique has not only the advantages of SMC, but also increases the stability performance of the system and speeds up the convergence rate near the equilibrium point [20,21]. In the recent years, a decoupled sliding mode control (DSMC) method has been planned which provides a simple procedure to decouple a class of fourth-order nonlinear systems into two second-order subsystems such that each subsystem contains a separate control purpose stated in terms of a switching surface [22,23]. A significant value of using DSMC is that the second subsystem is incorporated into the first subsystem by using a two-level decoupling scheme [24–26].

In the past decades, the super-twisting algorithm (STA) has been proposed as an alternative to conventional SMC technique [27–29]. STA scheme is extensively employed in various researches to

* Corresponding author. P.O. Box 38791-45371, Zanjan, Iran.
E-mail address: mobayen@znu.ac.ir (S. Mobayen).
URL: http://www.znu.ac.ir/members/mobayen_saleh

https://doi.org/10.1016/j.isatra.2018.02.006
0019-0578/© 2018 ISA. Published by Elsevier Ltd. All rights reserved.

decrease the chattering problem; because it does not require to measure the higher-order time-derivatives of the sliding surfaces [30,31]. STA is one of the most powerful second-order SMC algorithms introduced by Levant [32] which can handle a relative degree equal to one [33]. In general, STA creates a continuous control function which steers the sliding variable and its time-derivative to zero in the finite time in the existence of the smooth uncertainties with bounded gradient [34,35]. The algorithm guarantees robustness with regard to external disturbances and modeling errors while reducing the chattering problem originated in the conventional SMC [36]. Furthermore, STA obtains superior rapidity and stability to high-order SMC laws and prevents from acquiring the high-order derivative. STA has been effectively employed for several purposes such as state-estimation [37], tracking [38], synchronization [39], observation [40] and exact differentiation [41].

1.2. Literature review

In Ref. [42], a decoupled adaptive neuro-fuzzy DSMC scheme is proposed for the chaos control problem in a system without precise model information. However, the neuro-fuzzy DSMC control method of [42] is only applied for a Lorenz chaotic problem. A decoupled state-feedback and SMC technique is planned in Ref. [43] for three-phase PWM rectifier. Though, the proposed scheme of [43] is only employed for a three-phase PWM rectifier. Online optimal DSMC based on moving least squares and particle swarm optimization (PSO) procedures have been studied in Ref. [25]. But, the studied procedure in Ref. [25] has no analytical proofs for the stability of the controlled system. In Ref. [44], an adaptive robust PID control subject to supervisory DSMC based on genetic algorithm (GA) optimization approach is introduced. Nevertheless, reference [44] is based on a heuristic numerical algorithm. In Ref. [45], a DSMC technique is designed for a class of robots constituted by a chain of continuum segments named continuum arm. However, the dynamic equations of [45] are represented by a set of ordinary differential equations (ODE's) in time instead of partial differential equations (PDE's) in time and space. In Ref. [46], a disturbance estimator-based full-order DSMC method for a class of uncertain nonlinear multiple-input multiple-output (MIMO) systems is proposed. Though, the linear sliding surfaces have been used in the mentioned method of [46]. In Ref. [47], an adaptive neuro-interval type-2 fuzzy DSMC technique is applied on a three-dimensional crane system. Nevertheless, the parametric uncertainties are not considered in the three-dimensional crane model of [47]. Reference [22] suggests a nonsingular decoupled terminal sliding mode control (DTSMC) strategy for a class of fourth-order nonlinear systems. In Ref. [23], a time-varying sliding-coefficient-based DTSMC technique is presented for the fourth-order systems to make both subsystems converge to their equilibria in the finite time. In Ref. [48], a nonsingular DTSMC method is offered to address the tracking control problem of affine nonlinear systems. However, the adaptive approach has not employed in Refs. [22,23,48] for the estimation of the bound of external disturbances. A nonsingular DTSMC approach is planned in Ref. [26] for a three-degrees-of-freedom (3-DOF) parallel manipulator with actuation redundancy. Though, a radial basis function neural network (RBFNN) is applied to compensate the cross-coupling force and gravity of the parallel manipulator to improve the control precision. In Ref. [49], a tensor product model transformation based DTSMC design scheme is proposed. But, the parametric uncertainties have not been considered in the model of [49]. To the best of our knowledge, none of the studies mentioned above have been motivated on design of the adaptive decoupled terminal sliding mode control (ADTSMC) and adaptive super-twisting decoupled terminal sliding mode control (ASTDTSMC) schemes. Moreover, the authors believe that any research has not been investigated on the chattering-free adaptive decoupled terminal sliding mode control on fourth-order systems with nonlinearities, parametric uncertainties and external disturbances which eliminates the necessity of the information about upper bounds of perturbations.

1.3. Contribution

In this paper, an adaptive super-twisting decoupled terminal sliding mode control method is investigated for a class of perturbed fourth-order systems. The control scheme is designed based on the Lyapunov stability theory. Furthermore, an adaptive gain-tuning law is adapted in the proposed DTSMC scheme which estimates the unknown upper bounds of the parametric uncertainties and external disturbances. Using the super-twisting algorithm approach, the chattering problem can be removed without any effectiveness on the stabilization performance. The numerical simulation confirms high stabilization accuracy and lower values of performance indices for the proposed technique compared to the other methods. Lastly, the proposed method is employed on an experimental cart-pole system to confirm the success and efficiency of this scheme. The main innovations of this paper compared to the related investigations are listed as follows:

- An adaptive super-twisting decoupled terminal sliding mode control scheme is designed for the stabilization of fourth-order systems;
- A suitable adaptive parameter-tuning law is suggested to dominate the perturbations of the system without the information of their upper bounds;
- A novel control procedure is proposed to establish a chattering-free robust performance and finite time convergence for both subsystems;
- The proposed technique is verified by demonstrative simulation results and experimental assessments.

1.4. Paper organization

The paper is organized as follows: in Section 2, the formulation of the fourth-order (cart-pole) system is given. The novel ASTDTSMC technique is presented in Section 3 as well as the stability analysis of the uncertain fourth-order system. In Section 4, the numerical simulation and experimental results on cart-pole system are prepared. Lastly, Section 5 gives concluding remarks.

2. Problem formulation

The considered fourth-order (cart-pole) system is in the form of under-actuated dynamical systems. This class of systems has fewer actuators than the degrees of freedom to be controlled [50]. Under-actuated dynamical systems have significant applications such as under-water robots, overhead crane, free-flying spacecraft, robotic manipulators, hypersonic vehicles, etc [51,52]. The stabilizer and tracker design for such systems requires a wide investigation. In the recent decade, much attention has been considered for the stabilization and tracking control of under-actuated systems. Several control approaches such as H_∞ control, input-output linearization, neural networks, backstepping control, SMC and Lyapunov redesign have been proposed to design appropriate controllers for these systems [53,54]. The under-actuated systems have many advantages, which contain lightening the system, decreasing the actuators' number and reducing the construction cost [55,56].

Please cite this article in press as: Ashtiani Haghighi D, Mobayen S, Design of an adaptive super-twisting decoupled terminal sliding mode control scheme for a class of fourth-order systems, ISA Transactions (2018), https://doi.org/10.1016/j.isatra.2018.02.006