ISA Transactions 53 (2014) 33–43

Contents lists available at ScienceDirect

ISA Transactions

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

Research Article

Recurrent fuzzy neural network backstepping control for the prescribed output tracking performance of nonlinear dynamic systems

Seong-Ik Han, Jang-Myung Lee *

School of Electrical Engineering, Pusan National University, Jangjeon-dong, Geumjeong-gu, Busan 609-735, Republic of Korea

ARTICLE INFO

Article history:
Received 4 July 2013
Received in revised form
13 August 2013
Accepted 28 August 2013
Available online 20 September 2013
This paper was recommended for publication by Jeff Pieper

Keywords:
Prescribed tracking performance
Error constraint variable
Backstepping control
Recurrent fuzzy neural networks

ABSTRACT

This paper proposes a backstepping control system that uses a tracking error constraint and recurrent fuzzy neural networks (RFNNs) to achieve a prescribed tracking performance for a strict-feedback nonlinear dynamic system. A new constraint variable was defined to generate the virtual control that forces the tracking error to fall within prescribed boundaries. An adaptive RFNN was also used to obtain the required improvement on the approximation performances in order to avoid calculating the explosive number of terms generated by the recursive steps of traditional backstepping control. The boundedness and convergence of the closed-loop system was confirmed based on the Lyapunov stability theory. The prescribed performance of the proposed control scheme was validated by using it to control the prescribed error of a nonlinear system and a robot manipulator.

1. Introduction

For many industrial control systems, the performance constraints of control systems have received much attention, in terms of the type of physical stoppage, saturation, performance, and safety specifications to prevent performance degradation, hazards, or system damage. Some notable constraint techniques for position, velocity, and force constraints that exist in servo dynamic systems are the barrier Lyapunov function (BLF) technique [1–3] inspired by Brunovsky-type systems [4], the performance transformation function technique developed by Rovithakis et al. [5–7], Na et al. [8,9], and the funnel control technique proposed by Ilchman et al. [10,11] and Hackl et al. [12,13].

The BLF technique uses the logarithmic function in the Lyapunov function, and the state variable of the control system can be constrained by the symmetric, or asymmetric and time-invariant [1,2] or time-varying constraint [3] of the state variable. Therefore, the tracking errors can be indirectly constrained. On the other hand, the BLF controller must be redesigned to accommodate the change in the Lyapunov function and to establish the stability of the closed-loop system and bound condition parameters. A piecewise smooth BLF was also adopted in the asymmetric BLF design. Consequently, extra effort is needed to ensure the continuity and differentiability of the piecewise smooth stabilizing functions.

The approach proposed by Rovithakis et al. [5–7] and Na et al. [8,9] is to construct a prescribed performance function, and subsequently, to provide the inverse of a transformation function that converts the tracking error of an original nonlinear system into a new error in the transformed system. Therefore, the tracking performance of the transient property and the steady-state error can be characterized by a prescribed constraint function. However, a tangent hyperbolic function has been adopted as the transformation function that is combined with a prescribed smooth function to transform the tracking error. Therefore, the inverse transformation function, which would inevitably include a partial differential terms in the controller, may cause the singularity problem in controllers when implemented.

On the other hand, as a non-model-based (memoryless) constraint technique, the funnel control proposed by Ilchman et al. and Hackl et al. also guarantees the prescribed transient behavior, and asymptotic tracking of the system. This technique bypasses the difficulties of identification and estimation of traditional high-gain adaptive control. However, funnel control is limited, because it can only be applied to a class S of a linear or nonlinear system with a relative degree of *one* or *two* stable zero-dynamics (minimum-phase in the LTI case) and with a known positive high-frequency gain.

In this paper, we propose a new error-constraint variable for transient and asymptotic tracking that does not use the aforementioned complex transformation function and is not limited by a class S like the conventional funnel control. The error constraint variable is used as a virtual control variable in the backstepping design to ensure a prescribed transient and steady-state performance. A backstepping control provides guaranteed global or

* Corresponding author. Tel.: +82 51 510 2378; fax: +82 51 515 5190.
E-mail address: jmlee@pusan.ac.kr (J.-M. Lee).

0019-0578/$ - see front matter © 2013 ISA. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.isatra.2013.08.012

regional regulations and tracking properties and avoids the unnecessary cancellation of useful nonlinearities, unlike the feedback linearization technique. It also provides a systematic procedure for designing a stabilizing controller for a nonlinear system by following a step-by-step recursive algorithm [14,15]. However, this control undergoes the complex term of the controller because of the repeated differentiations of virtual control functions in recursive design procedures. A robust adaptive backstepping controller is then designed to ensure that the tracking error falls within the prescribed performance bounds and that all other signals of the closed-loop systems are continuously bounded in some small residual set. The RFNN system, which provides the benefits of both recurrent neural networks (RNNs) [16,17] and fuzzy logic systems [18,19], was considered to compensate for a large number of complex terms and to avoid the complexity of the controller.

The main contributions of this paper are as follows: (1) a proposed error performance variable to constrain the performance within the prescribed bounds by using a virtual backstepping control for a strict feedback nonlinear system; (2) a proposed error performance constraint that can handle the time-invariant and time-varying error constraints without using the complex barrier Lyapunov function, as used in [1–3]; (3) a proposed backstepping method for nonlinear systems that uses the RFNNs approximation to solve the problem of controller complexity, which is inherent in conventional backstepping control; (4) an evaluation of the proposed constrained backstepping method by simulation and experiment in a nonlinear system and a robot manipulator. The backstepping BLF-based constraint schemes [1–4], Transformation-function-based constraint scheme [5–7,8], and the funnel control [10,12,13] have been evaluated using only numerical demonstrations, and experiment was executed only in [9] and [11].

The rest of this paper is organized as follows. Section 2 outlines the nonlinear system dynamics, error constraint, and RFNN system. The formulation of the recursive backstepping controller with a prescribed error constraint and its stability analysis are discussed in Section 3. The controller′s performance is verified through simulation of a nonlinear system and experiment of the Scorbot robot manipulator. The results are illustrated and analyzed in Section 4. In Section 5, conclusions are finally summarized.

2. Motivating problem

2.1. Dynamics of a strict-feedback nonlinear system

Consider a strict-feedback nonlinear system whose dynamics can be described using the following equations:

$$\begin{aligned}\dot{x}_i &= f_i(\bar{x}_i)+g_i(\bar{x}_i)x_{i+1}+d_i, \quad 1 \le i \le n-1,\\ \dot{x}_n &= f_n(\bar{x}_n)+g_n(\bar{x}_n)u+d_n,\\ y &= x_1, \end{aligned} \tag{1}$$

where x_i is the state of the ith subsystem, $\bar{x}_i=[x_1, \ldots, x_i]^T \in R^i$ represent the vector of the partial state variables in the nonlinear system, $u \in R$ and $y \in R$ denote the control input and output of the system, respectively, $f_i(\bar{x}_i)$, $i=1,\ldots,n$, are unknown bounded smooth functions, and d_i, $i=1,\ldots,n$, are the uncertainties belonging to the compact set and are composed of the unmodeled dynamics and external disturbances. $g_i(\bar{x}_i)$, $i=1,\ldots,n$, are the smooth control gain functions and assumed to be bounded within the compact set $\Omega \in R^n$, where Ω can be made as large and as desired.

Assumption 1. The signs of g_i, $i=1,\ldots,n$, are strictly positive or negative. Without loss of generality, there exist positive constants $0<g_{i\,\min} \le g_{i\,\max}$ such that $g_{i\,\min} \le g_i(\bar{x}) \le g_{i\,\max}$, $\forall \bar{x}_n \in \Omega \subset R^n$.

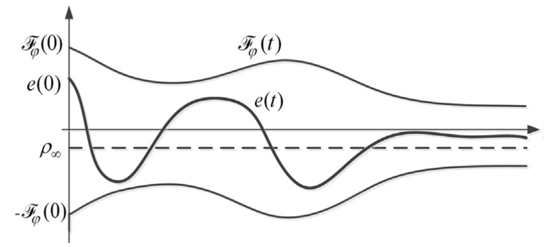

Fig. 1. Basic concept of funnel control.

If the signs of g_i are unknown, the Nussubaum function technique can be introduced in the backstepping design procedure [20].

Assumption 2. The desired trajectory signal $y_d(t)$ is available with its n time derivatives, piecewise continuous and the vector $\bar{y}'_d=[y_d, y_d^{(1)}, \ldots, y_d^{(i)}]^T$ is bounded.

The control objectives are:

1. Determine a state feedback control system such that the output x_1 of the system can track a desired trajectory y_d, while ensuring that all the solutions of the closed-loop system are semi-globally, uniformly, and ultimately bounded.
2. Ensure that the prescribed funnel performance bound for tracking error $e(t)=y(t)-y_d(t)$ is always satisfied.

2.2. Funnel control and the new error constraint virtual variable

Funnel control is a strategy that employs a time-varying gain $\tau(t)$ to control systems of class S with a relative degree $r=1$ or 2, stable zero dynamics, and known high-frequency gains. The system S is governed by the funnel controller with the control input

$$u(t)=\tau(F_\varphi(t), \psi(t), \|e(t)\|) \times e(t) \tag{2}$$

by evaluating the vertical distance at the actual time, as shown in Fig. 1, between the funnel boundary $F_\varphi(t)$ and the Euclidian norm $\|e(t)\|$ of error, as follows

$$d_v(t)=F_\varphi(t)-\|e(t)\| \tag{3}$$

The funnel boundary is given by the reciprocal of an arbitrarily chosen bounded, continuous and positive function $\varphi(t)>0$ for all $t \ge 0$ with $\sup_{t \ge 0}\varphi(t)<\infty$. The funnel is defined as the set

$$F_\varphi : t \to \{e \in R^m \,|\, \varphi(t) \times \|e\| < 1\} \tag{4}$$

The control gain of (2) is adjusted to ensure that the error $e(t)$ evolves inside the funnel $F_\varphi(t)$, as follows:

$$\tau(t)=\frac{\psi(t)}{F_\varphi(t)-\|e(t)\|}, \tag{5}$$

where $\psi(t)$ denotes the scaling factor. Thus, as the error $e(t)$ approaches the boundary $F_\varphi(t)$, the gain $\tau(t)$ increases, and as the error $e(t)$ becomes small, the gain $\tau(t)$ decreases conversely. A proper funnel boundary to prescribe the performance is selected by the following:

$$F_\varphi(t)=\xi_0 exp(-at)+\xi_\infty, \tag{6}$$

where $\xi_0 \ge \xi_\infty>0$, $\xi_\infty=\liminf_{t\to\infty} F_\varphi(t)$, and $|e(0)|<F_\varphi(0)$.

However, this funnel control is limited in class S, which requires the aforementioned conditions; therefore, we propose a new error constraint variable combined with virtual control of the backstepping scheme described in Section 3. In the backstepping scheme, any limitation required by class S of the funnel control is not imposed on the control system. In addition, a new