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Neural network observer-based networked control for a class of nonlinear systems

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ABSTRACT

A new neural network observer-based networked control structure for a class of nonlinear systems is developed and analyzed. The structure is divided into three parts: local linearized subsystem, communication channels and remote predictive controller. A neural-network-based adaptive observer is presented to approximate the state of the time-delay-free nonlinear system. The neural-network (NN) weights are tuned on-line and no exact knowledge of nonlinearities is required. The time delays considered in the forward and backward communication channels are constant and equal. A modified Smith predictor is proposed to compensate the time delays. The controller is designed based on the developed NN observer and the proposed Smith predictor. By using the Lyapunov theory, rigorous stability proofs for the closed-loop system are presented. Finally, simulations are performed and the results show the effectiveness of the proposed control strategy.

1. Introduction

Networked control system (NCS) is such a system that a remote controller communicates with a plant through two independent communication channels. NCSs have been used in a wide range of areas because of their advantages in practical applications such as reduced system wiring, eased maintenance and diagnosis, and increased flexibility [1].

The insertion of communication network also brings many challenging problems. The key one is the network-induced delay which may make the system unstable or demonstrate undesired performance. The network delay can be modeled as a constant delay, an independent random delay, and a delay with known probability distribution [2]. Many works have been made to solve these delay problems [3,4]. Different mathematical-, heuristic-, and statistical-based approaches are taken for different delay compensation [5]. A gain scheduler middleware (GSM) was proposed in [6] to alleviate the network delay effect. A new control scheme consisting of a control prediction generator and a network delay compensator was developed in [7]. A time-delay-compensation method based on the concept of network disturbance and communication disturbance observer has been proposed in [8]. Due to its no use of delay-time model, the method can be flexibly applied to many kinds of time-delayed control systems. Some methods consider NCS as a classical control system with slowly changing delay times and adopt well-known control methods such as the Smith predictor [8,9]. The queuing/buffering method turns the NCS into a time-invariant system to alleviate the delays. The constant network delay is considered in this paper.

To the best of our knowledge, most of the results about NCSs are based on linear systems [10,11], and only a few literatures focus on the nonlinear ones. Besides, most literatures consider the discrete-time systems [12]. In this paper, we consider a nonlinear continuous-time system which has uncertain nonlinear terms and unknown external disturbance. This type of system is closer to the practical one and owns a far worthier study.

In order to deal with the nonlinear terms, the neural network is proposed and widely used due to its versatile features such as learning capability mapping and parallel processing. A sliding-mode neural-network (SMNN) control system for the tracking control of robot manipulators to achieve high-precision position control was investigated in [13]. Two neural network-based controllers were designed for the teleoperation system in free motion in [14]. One is a new adaptive controller using the acceleration signal, another without the acceleration signal. In this paper, we employ the NNs to estimate the uncertainties.

In most practical situations, the velocity signals are always difficult to measure. Hence, an observer is imperative to estimate the state signals when we design the controller. A dynamic neural-network-based adaptive observer for a class of nonlinear systems was presented in [15], which does not require exact knowledge of nonlinearities. However, the output error equation in [15] is strictly positive real (SPR) which is a restrictive assumption for nonlinear systems. Therefore, paper [16] proposed a new observer without the SPR condition by introducing a vector b_0. Besides, more observer design methods have been proposed in [17–20].

In this paper, we consider the networked control design problem for a class of nonlinear systems with unknown nonlinear

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functions. The state variables of system could not be completely obtained. A NN observer is designed to estimate the unmeasurable state. The Smith predictor is employed to deal with the network induced time delay. Based on the constructed observer and the Smith predictor, we design the nonlinear controller to render that the system output follows the given reference signal. By constructing Lyapunov function, the stability of the closed-loop system is proved. Finally, simulations are performed to show the effectiveness of the proposed strategy.

This paper is organized as follows. The nonlinear system and the problem we discussed are presented in Section 2. Preliminaries about neural network are introduced in Section 3. A neural network observer and its stability analysis are presented in Section 4. In Section 5, we introduce the whole structure of the control strategy and design a neural network predictive controller. Finally, simulation results are presented in Section 6.

2. Background and problem formulation

In this paper, we discuss a class of single-input single-output (SISO) nonlinear systems with networked time delay as follows:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = x_3(t) \\ \vdots \\ \dot{x}_n(t) = f(x(t)) + g(x(t))u(t-T) + d(t) \\ y = x_1 \end{cases} \tag{1}$$

where $x(t) = [x_1(t)\ x_2(t)\ \cdots\ x_n(t)]^T \in R^n$, $u(t) \in R$, $y(t) \in R$ are the state, the control, and the output of the plant, respectively; $d(t)$ is the unknown disturbance with a known upper bound b_d; $f(x)$ and $g(x)$ are unknown smooth functions; T is the network induced time delay. The above equation can be expressed as

$$\begin{cases} \dot{x} = A_s x + b[f_0(x) + g(x)u(t-T) + d] \\ y = c^T x \end{cases} \tag{2}$$

where

$$A_s = \begin{bmatrix} 0 & 1 & & & \\ & \ddots & \ddots & & \\ & & \ddots & \ddots & \\ & & & 0 & 1 \\ -a_n & \cdots & \cdots & -a_2 & -a_1 \end{bmatrix}, \quad b = \begin{bmatrix} 0 \\ \vdots \\ \vdots \\ 0 \\ 1 \end{bmatrix}, \quad c = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ \vdots \\ 0 \end{bmatrix} \tag{3}$$

and $f_0(x) = f(x) + \sum_{i=1}^{n} a_{n-i+1} x_i$. The parameters a_i are suitably chosen such that A_s is stable. Given a symmetric positive definite matrix Q, there exists a symmetric positive definite matrix P_s satisfying the following Lyapunov equation:

$$A_s^T P_s + P_s A_s = -Q \tag{4}$$

In this work, we assume that there is a constant time delay T in the input channel and the feedback channel, and only the output signal y can be measured. Therefore, the first thing we do is to design a nonlinear observer to estimate the state which will be used in the design of the control input $u(t)$. Due to the constant time delay, the control input $u(t)$ can only be applied to the plant after a delay of T. In order to eliminate the influence of the time delay, we employ a modified Smith predictor which confirms the accurate output tracking of the system.

The control objective can be described as follows: given a desired state $x_d(t)$, design a neural network observer and a control $u(t)$ such that the observer state estimates the actual state exactly and both of them follow the delayed desired trajectory with an acceptable accuracy.

The desired trajectory vector is defined as

$$x_d(t) = [y_d(t)\ \dot{y}_d(t)\ \ldots\ y_d^{(n-1)}(t)]^T \tag{5}$$

For this purpose, we make some mild assumptions as follows:

Assumption 1. The desired trajectory vector $x_d(t)$ is continuous and available for measurement, and $x_d(t)$ is bounded.

Assumption 2. The time delay T is a known constant, and the time delay in the input channel is equal to that in the feedback one.

Assumption 3. There exist constant $g_0 > 0$, and known smooth function $g_d(x)$ such that $g_d(x) \geq |g(x)| \geq g_0$.

Remark 1. Assumption 3 implies that the smooth function $g(x)$ is strictly either positive or negative. It is reasonable because being away from zero is a controllable condition of system (1), which is made in most control schemes. For a given practical system, the upper bound of $g(x)$ is not difficult to determine by choosing $g_d(x)$ large enough. Besides, the low bound g_0 is only required for analytical purpose, so its true value is not necessarily known.

Definition 1. We say that the solution of a dynamic system is uniformly ultimately bounded (UUB) if for a compact set U of R^n and for all $x(t_0) = x_0 \in U$ there exists an $\varepsilon > 0$ and a number $T(\varepsilon, x_0)$ such that $\|x(t)\| < \varepsilon$ for all $t \geq t_0 + T$.

Remark 2. Neural network predictive control strategies for nonlinear dynamic systems and telerobot are presented in [21] and [22], respectively. The systems considered are simpler than that we discuss in this paper. What is more, all the state variables are required to be available in the literatures, which is not the case in most practical systems. In this paper, we discuss the situation that not all states can be measured.

In this paper, we denote $\|\cdot\|$ as the Euclidean norm, and $\|\cdot\|_F$ as the Frobenius norm.

3. Preliminaries

In the control engineering, RBF neural network is usually used as a tool for modeling nonlinear functions because of their good capabilities in function approximation. The RBF neural network can be considered as a two-layer network in which the hidden layer performs a fixed nonlinear transformation with no adjustable parameters, i.e., the input space is mapped into a new space. The output layer then combines the outputs in the latter space linearly. Therefore, they belong to a class of linearly parameterized networks. In this paper, the following RBF neural network is used to approximate the continuous function $f(x(t)) : R^q \to R$:

$$\hat{f}(x(t)) = \hat{W}^T \Phi(x(t)), \tag{6}$$

where the input vector $x \in Q_x \subset R^q$, and q is the neural network input dimension. Weight vector $\hat{W} = [\hat{W}_1, \hat{W}_2, \ldots, \hat{W}_l]^T \in R^l$, the NN node number $l > 1$, and $\Phi(x(t)) = [\Phi_1(x(t)), \ldots, \Phi_l(x(t))]^T$, with $\Phi_i(x(t))$ chosen as the commonly used Gaussian function, which is in the following form:

$$\Phi_i(x(t)) = \exp\left[\frac{-(x(t)-\mu_i)^T (x(t)-\mu_i)}{2\eta_i^2}\right], \tag{7}$$

where $\mu_i = [\mu_{i1}, \mu_{i2}, \ldots, \mu_{iq}]$ is the center of the receptive field and η_i is the width of the Gaussian function.

It has been proven that the neural network can approximate any continuous function over a compact set $\Omega_x \subset R^q$ to arbitrary accuracy as

$$f(x(t)) = W^T \Phi(x(t)) + \varepsilon(x), \quad \forall x \in \Omega_x, \tag{8}$$