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Multivariable adaptive neural network predictive control in the presence of measurement time-delay; application in control of Vinyl Acetate monomer process

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ABSTRACT

As an integral part of a plantwide control system for large-scale nonlinear systems with non-measurable states and time-delay in measured outputs, a multi-input multi-output (MIMO) adaptive neural network predictive controller (ANNPC) is presented. A neural network model-based observer is used in the structure of the proposed controller to estimate the unknown states. Then, an adaptive predictor is designed based on the observer and is employed to predict non-measurable states. Stability of the proposed observer and controller is proved using Lyapunov function theorem. The proposed controller is used as a part of the control system of a Vinyl Acetate monomer (VAM) process. A new partially-centralized structure is developed for plantwide control of the process and the efficiency of the proposed controller particularly in diminishing the effect of measurement time-delay is shown, in-silico, by numerical simulation of a VAM plant under control. The obtained results are compared with the results of the conventional PI-based control system of VAM process.

1. Introduction

Chemical processes are usually consisted of a number of processing units and thousands of measurements and manipulated variables. Plantwide control is a method which facilitates the control system design for such large-scale systems; it also affects the selection of controlled (CV's) and manipulated variables (MV's), input-output variables (loop pairing), controller structure (centralized and distributed), and the implementation of control systems for each plant and for the whole plant [1]. Control analysis and design methods used for large-scale systems can be classified into centralized and distributed control strategies. In recent decades, there has been much interest in the development of new theories about centralized and distributed controllers in large-scale multi-input multi-output (MIMO) systems. For systems with weak or modest interactions, distributed control can generally show satisfactory performance, whereas for systems containing strong interactions, its performance might be deteriorated. On the other hand, a centralized controller can handle the strong interactions and can increase the process robustness against external disturbances, model uncertainty, etc. [2–4], although it may greatly increase the computational costs and complexity. Hence, the selection of the structure of plantwide control system for large-scale processes is important and interesting.

On the other hand, the dynamical behavior of many chemical processes is considerably affected by the time-delay attributed to transportation lags and measurement delays. The presence of time-delay may cause instability in a closed-loop system, severe limitation on achievable control performance, and sluggish response [5,6]. After that Smith [7] proposed the classical Smith predictor for stable linear systems, the identification and control of time-delay systems has been studied extensively in the literature [8–12]. A small number of time-delay compensation methods are available for nonlinear time-delay systems, most of which are invalid for time-delay compensation of unknown nonlinear systems [13,14]. To overcome this problem, adaptive methods such as predictor-based methods that are developed based on neural network (NN) and fuzzy models, are proposed in the literature [8,14–23], some of which are focused on unknown and nonlinear MIMO time-delay systems [17–23].

Considering high-dimensional large-scale processes as a single MIMO system in a centralized control structure, leads to greatly increased computational complexity and makes the predictor and controller difficult or even impossible to be implemented [24]. A

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Nomenclatures

CV	Controlled variable
G	Linear system
Inf(.)	Infimum operator
$\mathbf{K}$	Constant feedback gain matrix
K_P	Proportional gain of PI controller
K_I	Integral gain of PI controller
L	Lyapunov function
MV	Manipulated variable
N	Nonlinear system
p_A	Partial pressure of HAc (psia)
p_E	Partial pressure of C_2H_4 (psia)
p_O	Partial pressure of O_2 (psia)
p_w	Partial pressure of H_2O (psia)
proj(.)	Projection operator
Q_C	Compressor heater duty (kcal/min)
Q_{CIR}	Circulation cooler duty (kcal/min)
Q_i	Energy used per a unit (kj/h)
Q_{SCR}	Scrub cooler duty (kcal/min)
r_1	Units of moles of VAM produced (mol/min/g catalyst)
r_2	Units of moles of C_2H_4 consumed (mol/min/g catalyst)
Sup(.)	Supremum operator
t	Time
T	Reactor temperature (K)
tr(.)	Trace of matrix
$\boldsymbol{u}$	Input vector
$u_{N,in}$	Inputs of the nonlinear process
$\boldsymbol{x}_{G,0}$	Initial condition of the linear system
$\boldsymbol{x}_N$	States
$\boldsymbol{x}_{N,0}$	Initial condition of the nonlinear system
$\hat{x}$	Estimated states
$\tilde{x}$	States estimation error
$\boldsymbol{x}_P$	Predicted states
$\boldsymbol{y}$	Output vector
$\hat{y}$	Estimated outputs
$\tilde{y}$	Outputs estimation error
$\boldsymbol{y}_d$	Eference outputs
$\boldsymbol{y}_P$	Predicted output
$\boldsymbol{W}$	NN weight matrix

Greek symbols

τ	Measurement time-delay
$\boldsymbol{\varepsilon}$	Bounded error
$\phi(.)$	NN transfer function
$\sigma(.)$	Sigmoid function
λ	Eigenvalue
∇	Gradient operation
$\phi_N^{y_a}$	Nonlinearity measure

solution for this problem, which is discussed in this paper, is to design a partially-centralized structure for plantwide control system in which the highly interconnected subsystems are considered as MIMO subsystems [25], and the CV's and MV's with weak or modest interactions are pared in a single-input single-output (SISO) manner.

In this work, as an integral part of a plantwide controller for nonlinear large-scale systems with measurement time-delay, an adaptive neural network predictive controller (ANNPC) is designed, which is applicable for nonlinear MIMO subsystems with time-delays in their measured outputs. The partially-centralized structure can be designed based on input-output sensitivity analysis and identifying the high interaction subsystems of the large-scale nonlinear system. High order neural networks (HONN's) are used to approximate unknown functions of the nonlinear MIMO subsystems. One of the most important advantages of the on-line NN predictors is to reduce the computational cost of state estimation and prediction, due to recording a history of nonlinear system's dynamical behavior in the trained NN's (i.e. the observers and predictors), without iterative predictive calculations. The NN models are trained as observers for the required states of the MIMO subsystems and NN predictors are constructed based on the trained NN models. The proposed control rule for each subsystem is constructed based on the states estimated by the NN predictor. The stability of the proposed controller is ensured by analyzing a Lyapunov function.

The proposed plantwide control system is designed and applied, *in-silico*, for a Vinyl Acetate monomer (VAM) process, which is known as a challenging benchmark for nonlinear large-scale systems. The research activity on VAM process was mostly focused on dynamic simulation, designing the control structure, and plantwide control with implementation of classical PI-based control systems. The first presentation of the design details of an industrial VAM process comes from Luyben, et al. [26] where a first-principle-based model was introduced for VAM process. Chen, et al. [27] designed a plantwide control system for VAM process based on a linear dynamic model and output optimal control. The focus was on the loop pairing between the CV's and MV's. Olsen, et al. [28] presented a 2 × 2 Model Predictive Controller (MPC) for azeotropic distillation column of a VAM Process without considering the whole process. Seki, et al. [29] introduced a new distributed structure for the control system of a VAM process to obtain the optimal operating condition. Luyben [30] proposed an optimized design for the process and developed a new plantwide control structure to provide effective disturbance rejection. Psaltis, et al. [31] applied a new regulatory control structure selection methodology on the benchmark case study of the VAM plant and obtained a new structure of PI controllers. Tu, et al. [32] replaced five PI controllers of a PI-based traditional control system with five SISO Lyapunov-based MPC's acting on five manipulated inputs which directly affect an economic measure defined for the process. All of the above-mentioned plantwide control systems have used only PI controllers, except for [32], which used five SISO Lyapunov-based MPC's instead of five PI controllers. However, all of the mentioned controllers are SISO controllers in completely distributed structures.

In this study, first, the structure of the plantwide control system of the VAM process is selected based on an input-output sensitivity analysis of the CV's and MV's of the process. Based on the sensitivity analysis, the high-interaction MIMO subsystems of the process are identified and the proposed ANNPC is employed for them. The remaining control loops are considered to be SISO and they are controlled by PI controllers. The ANNPC is a rapid and simple controller; rapidity leads to real-time applications, and simplicity limits the risk of controller failures that may arise with the numerous PI controllers in large-scale plants and increases the reliability of the whole control system. The performance of the proposed control system is compared with that of the traditional PI-based control system used at the same plant.

The main contributions of this paper are the following:

- The ANNPC is designed for unknown and nonlinear MIMO systems with measurement time-delays and unknown external disturbances, and its stability is shown by a Lyapunov function approach. In a partially-centralized control structure of a large-scale system, the unknown external disturbances are forced to the MIMO subsystems from the states outside the subsystem. Similar works on this class of systems are reported for SISO systems and