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State and disturbance observers-based polynomial fuzzy controller

Hugang Han[a,*], Jiaying Chen[a], Hamid Reza Karimi[b]

[a] Department of Management and Information System, Prefectural University of Hiroshima, Hiroshima 734-8558, Japan
[b] Department of Mechanical Engineering, Politecnico di Milano, 20156 Milan, Italy

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ABSTRACT

It is important to account for the gap between the dynamics of a plant to be controlled and its mathematical model to improve the control performance. Hence, a controller is designed based on this. In this study, the gap is termed as a lumped disturbance, and is considered with respect to the polynomial fuzzy model that is more effective to represent the plant dynamics. More specifically, a design of state observer is first proposed under the existence of the lumped disturbance, and this is then followed by the proposal of a disturbance observer to estimate the lumped disturbance for further use in the controller design. Finally, a controller is developed for the case in which the control state as well as the lumped disturbance are unavailable. Additionally, computer simulations are provided to illustrate the effectiveness of the proposed approach.

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1. Introduction

Recently, polynomial fuzzy models [35] were used to synthesize controllers in fuzzy control systems in which sufficient conditions for system stability in the sense of Lyapunov stability were provided by solving certain sums of squares (SOS). These conditions could be numerically solved using existing solvers in literature, see for instance [24].

The polynomial fuzzy model can be viewed as an extension of the widely used T-S fuzzy models [31] in which the consequent of each fuzzy rule is in the form of state-space representation that is a linear differential equation. In contrast to the T-S fuzzy model, the polynomial fuzzy model allows local dynamics in the consequent of each fuzzy rule to be represented in the form of state-dependent representation that involves polynomial matrices and vectors of monomials in the control state. Therefore, the consequent of each fuzzy rule in the polynomial fuzzy model is basically nonlinear because of the polynomial matrices and monomial vectors involved. This implies that the polynomial fuzzy model involves more descriptive capability in terms of representing plant dynamics to be controlled that are often nonlinear. However, this type of a descriptive capability in the polynomial fuzzy model does not imply that there is no gap or modelling error between plant dynamics and the corresponding polynomial fuzzy model. Essentially, the modelling error includes external/internal disturbances, parameter perturbations, and unmodelled dynamics. In this study, the modelling error is referred to as a lumped disturbance. Evidently, it is necessary to account for the lumped disturbance when designing a controller to improve control performance. Otherwise, it is not possible to guarantee the desired control performance when the controller is applied to a real system if the lumped disturbance is significantly large.

* Corresponding author.
E-mail addresses: hhan@pu-hiroshima.ac.jp (H. Han), hamidreza.karimi@polimi.it (H.R. Karimi).

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In order to cope with the lumped disturbance in control systems, H_∞ control [16] is an effective approach that confines the influence of the disturbance to certain prescribed indices. However, a wide range of topics including tracking control [20], time-delay [40] and disturbance attenuation [39] were reported, and as a result, the disturbance effect existed in the steady-state response, and the influence to the control state was in proportion to the disturbance level. Conversely, from the viewpoint of the lumped disturbance as an unknown input, extant literature has proposed several state observer designs with unknown inputs [2,6,7,12,15,18,30,44] that focus on decoupling the influence of the unknown input from that of the state observer. Hence, when designing a model-based controller in the presence of an unknown input, the influence of the unknown input on the real state must be considered again, though the influence to the state observer was cancelled by multiplying the gain of the disturbance with an elaborately designed matrix.

In contrast, disturbance observer-based control provides a promising approach to handle the disturbance and improve robustness [5,14,19,23,26,38,45]. To-date, various techniques for this problem were either proposed or practiced such as a perturbation observer [17], an equivalent input disturbance based estimator [27,28], and an uncertainty and disturbance estimator [4,36,46]. Recently, a few studies examined the lumped disturbance using a polynomial fuzzy model [8–11]. However, all the fore-mentioned approaches treated the state as available, and this may limit its applications. Based on the above observation, it is desirable to estimate the lumped disturbance as well as the state such that such estimates can be directly used in the controller design from the control viewpoint.

In case of the control state that is unavailable in a control system, it is always necessary to design a state observer prior to the design of a controller. With respect to the T-S fuzzy model case, the separation property exists and implies that the stability of the entire system is maintained by separately designing the observer and controller [13]. However, this type of a separation property is no longer applicable in the polynomial fuzzy model case. Therefore, it is more challenging to design a state observer-based controller when the polynomial fuzzy model is used instead of the T-S fuzzy model. Recently, there were significant advances in studying observers based on the polynomial fuzzy model. Tanaka et al. proposed observer designs for a few specific cases of polynomial fuzzy models [32,33]. Based on the application of the Taylor-series methodology, Sala et al. suggested a fuzzy polynomial-in-membership model wherein fuzzy polynomial observers were proposed [25]. Liu et al. proposed polynomial fuzzy observer-controllers considering premise variables that could not be measured [21,22]. More recently, Chibani et al. proposed a polynomial fuzzy observer design for a model with unknown inputs [6]. To the best of the authors' knowledge, very few studies examined state/disturbance observers-based control design for polynomial fuzzy models, and this forms our motivation for the present study.

Given the aforementioned issues, in this study we first present a state observer design under the existence of a lumped disturbance. A design of a disturbance observer is then proposed based on the assumption that the control state is unavailable to counteract the disturbance in the controller design. This is followed by the development of a state-based and disturbance-based controller. Additionally, a practical way to overcome the difficulties of the unholding separation property is provided as a theorem. Finally, computer simulations are performed to illustrate the effectiveness of the proposed approach.

2. Polynomial fuzzy model

A nonlinear system is considered with dynamics expressed by the following polynomial fuzzy model:

Plant Rule i :

If $\theta_1(t)$ is M_1^i and $\cdots$ and $\theta_p(t)$ is M_p^i, Then

$$\left.\begin{aligned} \dot{x}(t) &= A_i(x(t))x(t) + B_i(x(t))\big(u(t)+d(t)\big) \\ y(t) &= C_i x(t) \\ \dot{y}(t) &= C_i \dot{x}(t) \end{aligned}\right\} \tag{1}$$

where $\theta_j (j = 1, 2, \cdots, p)$ denotes a variable in the antecedent; $M_j^i (i = 1, 2, \ldots, n_r)$, denotes a fuzzy term corresponding to the ith fuzzy rule; $x(t) \in R^n$ denotes the state vector that is assumed as completely unavailable for the purposes of the present study; $y(t), \dot{y}(t) \in R^r$ denotes the output vector and its time derivative; $A_i(x(t)) \in R^{n \times n}$ and $B_i(x(t)) \in R^{n \times m}$ denote the polynomial matrices in $x(t)$. Furthermore, $d(t) \in R^m$ denotes the disturbance including modelling error, external disturbance, unmodelled dynamics, and parameter perturbations. This is referred to as the lumped disturbance in this study.

As a result of defuzzification, $\dot{x}(t)$, $y(t)$ and $\dot{y}(t)$ in the polynomial fuzzy model can be represented as follows:

$$\left.\begin{aligned} \dot{x}(t) &= \sum_{i=1}^{n_r} \alpha_i(\theta(t))\Big(A_i(x(t))x(t) + B_i(x(t))\big(u(t)+d(t)\big)\Big) \\ y(t) &= \sum_{i=1}^{n_r} \alpha_i(\theta(t)) C_i x(t) \\ \dot{y}(t) &= \sum_{i=1}^{n_r} \alpha_i(\theta(t)) C_i \dot{x}(t) \end{aligned}\right\} \tag{2}$$

where

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