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Improved Takagi–Sugeno fuzzy model-based control of flexible joint robot via Hybrid-Taguchi genetic algorithm

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ABSTRACT

In this paper Takagi–Sugeno (T–S) fuzzy approach is used for control of a flexible joint robot (FJR). The control method in this paper is based on parallel distributed compensation approach (PDC). In this method, a state feedback controller is designed using a fuzzy model that consists of a set of linear fuzzy local models. These fuzzy local models are combined to get an overall fuzzy inference mechanism. In order to improve the efficiency of the system and to set the parameters of the controller the Hybrid-Taguchi genetic algorithm (HTGA) is used. The use of orthogonal arrays (OA) speeds up the convergence of the algorithm and the contribution of signal to noise (S/N) ratio will result in a more appropriate response. The stability of the controller is analyzed and finally it is implemented on the plant. The experimental results confirm the efficiency of the proposed intelligent method in controlling FJRs. Therefore, it can be considered as a proper method in controlling systems that are based on flexible robot arms.

1. Introduction

Most of the practical engineering control problems deal with nonlinear systems or systems with uncertain parameters. Flexible joint robot (FJR) is classified as an important part of nonlinear systems and is a lightweight robotic arm usually used in aerospace researches, military and engineering structures. Analyzing and controlling such a nonlinear system based on its model via classic control methods is a complicated problem and depends on model accuracy (Dwivedy and Eberhard, 2006). Therefore modeling the nonlinear system plays a significant role in the control procedure. In 1997, Yim, Oh and Lee proposed output feedback controller to control flexible joint in Yim (2001) and Oh and Lee (1997). Fateh (2012) introduced feedback controller for FJR by linearization technique. Up to now, many attempts have been made to control the link of FJR including nonlinear, robust, adaptive and intelligent methods. Taghirad and Khosravi in Taghirad and Khosravi (2000) have used PID controller. Adaptive control has been introduced by khorasani and Ghorbel et al. in Seidi and Markazi (2008). Akyuz and his coworkers in Akyuz et al. (2011) have studied fuzzy logic control of flexible joint manipulator and in Ahmad et al. (2010) PD fuzzy logic has been applied to control FJR. Seidi and Markazi (2008) have investigated fuzzy control of flexible joint and it has been developed by linear matrix inequality analysis. Therefore nowadays there are different intelligent approaches in modeling nonlinear systems such as fuzzy controllers and among them T–S fuzzy modeling approach is considered as one of the most practical methods (Hosseinpour et al., 2013). In T–S fuzzy method, nonlinear equations can be expressed through fuzzy rules and the stability analysis of this method has been investigated in many researches (Tanaka and Wang, 2004).

The history of T–S fuzzy model-based control goes back to 1985 when Takagi and Sugeno introduced a new type of fuzzy model representation for the first time (Bilgiç et al., 2003). T–S fuzzy modeling is represented through fuzzy if-then rules. The model is obtained by linearization of a nonlinear plant around different operating points. Next step is to design a local state feedback controller for each of the linear models. All these fuzzy rules along with each local controller result in a generally nonlinear modeling algorithm and a T–S fuzzy controller design (Tanaka and Wang, 2004).

As it was mentioned above, flexible joint robots are generally nonlinear systems that require certain controllers with especial designing methods. Moreover, the model of FJR, like any other electromechanical systems, has uncertainties due to the existence of tolerance in some physical parameters. Disturbance and the model uncertainties lead to low performance of controllers and a district region of convergence. The objective of this paper is to control FJR via parallel distributed control (PDC) approach. The history of PDC approach goes back to Tanaka and Sugeno researches and represents a method to design a fuzzy controller based on T–S fuzzy modeling. In this approach, each of the PDC control rules is in a close

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relationship with its T–S fuzzy model-based rule (Tanaka and Wang, 2004). In other words, PDC method helps us to design a state feedback controller using a fuzzy model that consists of a set of linear fuzzy local models. These fuzzy local models are combined to get an overall fuzzy inference mechanism. Therefore the main idea of designing such a controller is to derive sub-systems that consist of control rules. The stability analysis and control design problems are accomplished by LMIs and the stability conditions are analyzed via Lyapunov stability theory. This method can be used to solve many continuous and combinational optimization problems (Bilgiç et al., 2003).

In this paper, the procedure of controller design for T–S fuzzy model of FJR is optimized via HTGA in order to minimize a cost function including a quadratic integral. HTGA is an algorithm for solving optimization problems and was first introduced by Genichi. Therefore, using HTGA in the T–S fuzzy controlling method can result in an optimal controller (Tsai et al., 2004). Article continues in Section 2 with an explanation about T–S fuzzy modeling and the controller design via PDC approach. Section 3 includes an introduction on Taguchi method and explains HTGA that is used in order to optimize the parameters of the controller. In Sections 4 and 5, FJR and its equations will be studied in order to apply the previous sections on the system and also to investigate the stability. Finally, the experimental results are proposed in Section 6.

2. T–S fuzzy

T–S fuzzy modeling approach is a multi model approach that consists of simple sub-models. These sub-models are combined in order to describe the global behavior of the nonlinear system. The sub-models are typically linear and can be easily derived from the physical model of the given nonlinear system (Ho et al., 2006).

In order to get more familiar to T–S fuzzy modeling method consider a nonlinear system as in (1).

$$\dot{x} = F(x) + b(x)u \tag{1}$$

Where $x = [x_1, x_2, \ldots, x_n]^T$ is the state vector. $F(x)$ and $b(x)$ are the nonlinear functions of the plant, u is the control signal. $u(t) = [u_1(t), u_2(t), \ldots, u_p(t)]^T$.

The ith ($i = 1, \ldots, r$) IF-THEN fuzzy rule is in the following form:

$$\tilde{R}_i: \text{ If } Z_1(t) \text{ is } M_{i1} \text{ and} \ldots \text{and } Z_g(t) \text{ is } M_{ig}$$

$$\text{then} \begin{cases} \dot{x}(t) = A_i x(t) + B_i u(t) \\ y(t) = C_i x(t) \end{cases} \tag{2}$$

where r is the number of fuzzy rules, M_j is the grade of memberships of $Z_g(t)$, $Z_g(t)$ is fuzzy set, g is the number of nonlinear terms that are defined as $[Z_1(t), \ldots, Z_g(t)]$, A_i and B_i are the $n \times n$ and $n \times p$ constant state matrixes.

$$\dot{x}(t) = \frac{\sum_{i=1}^{r} w_i[Z(t)][A_i x(t) + B_i u(t)]}{\sum_{i=1}^{r} w_i[Z(t)]}$$

$$\mu_i[Z(t)] = \frac{w_i[Z(t)]}{\sum_{i=1}^{r} w_i[Z(t)]}$$

$$\Rightarrow \dot{x}(t) = \sum_{i=1}^{r} \mu_i[Z(t)][A_i x(t) + B_i u(t)] \tag{3}$$

w_i is the weight in its corresponding membership function, $w_i[Z(t)] = \prod_{j=1}^{g} F_j[Z_j(t)]$ and $F_j[Z_j(t)]$ is the membership grade of $Z_j(t)$ in jth fuzzy set.

The final state vector of fuzzy system and the output is represented as

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{r} \mu_i A_i x(t) + \sum_{i=1}^{r} \mu_i B_i u(t) \\ y(t) = \sum_{i=1}^{r} \mu_i C_i x(t) \end{cases} \tag{4}$$

One approach to control T–S fuzzy system is the PDC method. In this method, the output of fuzzy controller has the same rules as its T–S fuzzy model (Ho and Chou, 2007).

Fuzzy controlling rules are used to control the system and the weighted averages of linear subsystems can be obtained according to the equations of the main system (Tanaka and Wang, 2004).

Considering Eq. (2), design of the controller via PDC method results in the following form:

$$\text{If } Z_1(t) \text{ is } M_{i1} \text{ and } Z_2(t) \text{ is } M_{i2} \ldots \text{and } Z_g(t) \text{ is } M_{ig}$$

$$\text{then } u(t) = -K_i x(t), \quad i = 1, 2, \ldots, r \tag{5}$$

The output of the fuzzy state feedback controller is $u(t) = -\sum_{i=1}^{r} \mu_i[Z(t)] K_i x(t)$ where the eigenvalues of $A_i - B_i K_j$ are placed on left half-plane.

By substitution of (5) in (2)

$$\dot{x}(t) = \sum_{i=1}^{r} \sum_{j=1}^{r} \mu_i \mu_j (A_i - B_i K_j) x(t) \tag{6}$$

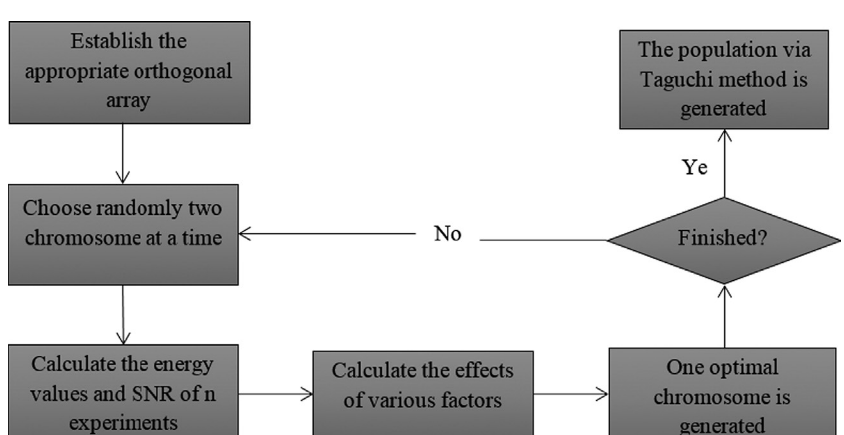

Fig. 1. The flowchart of the Taguchi method (Taguchi et al., 2004).