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A CONJUGATE GRADIENT TECHNIQUE FOR OPTIMAL FUZZY LOGIC CONTROL OF HIGHLY COMPLEX DYNAMIC SYSTEM

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ABSTRACT

The paper presents a novel approach for the application of adaptive fuzzy logic control algorithm. The aim of this adaptive system is to minimize an objective function in the output error via varying the center of each label. The model inependency characteristics of the fuzzy controller allows simple calculation and low implementation cost which are highly recommended features in control industry. A conjugate gradient technique is applied in this paper to minimize the error in least square sense. A real time nonlinear dynamic system is used to ensure the effectiveness of the proposed control scheme.

KEYWORDS : Conjugate gradient technique, Optimal fuzzy logic control.

1 INTRODUCTION

In the past years, optimal control problem has received a great attention Many control techniques have been developed to obtain high operating performnce [1-3]. Optimal control problem often involve finding a control action subject to certain constraints,which minimize some prescribed performance. This technique is needed in case where some physical behaviors are hard to be represented mathematically. The error in predicting the output performance under any condition would be at the designer's hand. However, these approches have the drawback of not being able to deal with non-linear system, [4-5].

In general, the human knowledge of the system is based on the experience and expertise inuition knowledge of the system's physical behavior. This type of knowledge is expressed in the form of liguistic rules. In this regard, a fuzzy logic controller is a knowledge-based controller. Fuzzy logic controller is useful just because of its low specificity,it allows a more flexible response to a given input. The output of a fuzzy system is smooth and continuous,ideal for the control of continuously variable systems [6-8]. Fuzzy systems base their decisions on inputs in the form of linguistic variables, the variables are tested with a small number of IF-THEN rules, which produce one or more responses depending on which rules were asserted. The response of each rule is weighted according to the confidence or degree of membership of its inputs,and the centroid of the responses is calculated to generate the appropriate output.

In this paper, an approach for the application of adaptive fuzzy logic control algorithm is given . This adaptive system is trying to minimize an objective function in the output error for which the center of each label could be varied. This allows simple calculation and low implementation cost which are highly recommended features in control industry. The aim of this study is to present a fuzzy logic controller, for any dynamic system, that needs

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neither nonlinear nor linear mathematical model. The only measurements required for the control design are the output error and the change in the output error [9,10,17,18].

This paper is organized as follows,in section 2, the fuzzy control system is given pointing out the structure of fuzzy controller. In section 3, fuzzy optimization is given, the dynamic equations of the proposed system as well as a test case are given in section 4. In section 5, a final conclusion is given.

2 FUZZY LOGIC SYSTEMS

Fuzzy logic systems are systems whose output behaviors ors are expressed by fuzzy concepts and fuzzy logic. These systems may be classified into three types; pure fuzzy logic systems, Takagi and Sugeno's fuzzy system, and fuzzy logic systems with fuzzifier and defuzzifier [7,11,12]. This paper, the last type will be considered.

2.1 FUZZY LOGIC SYSTEM STRUCTURE

The fuzzy logic system with fuzzifier and defuzzifier has many attractive features. First, it is suitable for Engineering Systems because its input and output are real-valued variables. Second it provides a natural framework to incorporate fuzzy IF-THEN rules from human experts. Finally, there is much freedom in the choice of fuzzifier, fuzzy inference engine, and defuzzifier. This fuzzy logic system is often called fuzzy logic controller [11-16].

2.1.1 FUZZY LOGIC CONTROLLER (FLC)

The FLC controller belongs to a general class of fuzzy logic system in which control variables are transformed into fuzzy sets *(FUZZIFICATION)* and manipulated by an inference engine in a collection of *(IF-THEN)* fuzzy rules. These rules are derived from the knowledge of experts with substantial experience, [9].

In general, the control engineer's knowledge of the system is based on expertise, intuition and knowledge of the system's behavior. Therefore, the main objective of the fuzzy control scheme is to replace an expert human operator with a fuzzy rule-based control system. The fuzzy-logic control (FLC) comprises three stages namely fuzzifier, rule-base and defuzzifier. Fig. (1) shows how the three stages are interacted.

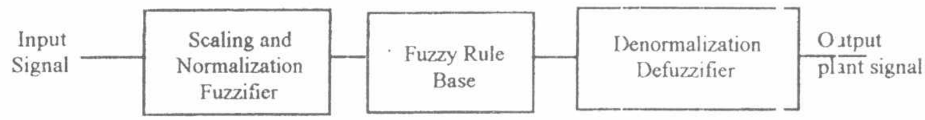

Fig.(1) The basic configuration of a Fuzzy logic controller.

A fuzzy logic controller is composed of input-output relation rules and these simple rules can deal with vague and complex situations. This proposed FLC structure is shown in Fig. (2)

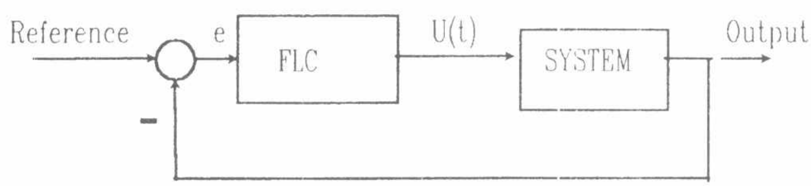

Fig. (2) FLC Block Diagram

2.1.2 FUZZY CONTROL ALGORITHM

To provide an acceptable overall performance, the FLC system must have quick response with small steady state error, therefore, the proposed rule base depends on the following concepts:

- The fuzzy controller maintains the output value when the output value is a set value and the error change is zero.
- Depending on the magnitude and sign of the speed error and speed error change the output value will return to the set value.

The error e and error change Δe are defined as a difference between the set-point value $\Delta\omega_r$ and the current output value $\Delta\omega_c(.)$

$$e(k) = \Delta\omega_r(k) - \Delta\omega_c(k) \qquad (1)$$

and

$$\Delta e(k) = e(k) - e(k-1)$$
$$= \Delta\omega_r(k-1) - \Delta\omega_c(k)$$

That is,

$$\Delta\omega_r(K) = \Delta\omega_r(K-1) = constant$$

Where :

$\Delta\omega_r(k)$ is the reference speed at k-th sampling interval $\Delta\omega_c(k)$ is the speed signal at k-th sampling interval $e(k)$ is the error signal. $\Delta e(k)$ is the error change signal.

The workable range is divided into intervals these intervals are named for example, positive, zero and negative. These names for the intervals are called labels. Each label is equipped with a weighting function called membership function. The rules relate the input variables to the output of the fuzzy controller. These rules can be expressed in a table with inputs on the horizontal and vertical cartesian axes. however the output would be inside each cell as shown in table (1)

Table 1 Rule table

Δe/e	P	Z	N
P		P	
Z		Z	
N		N	

Hence the control law can be formalized as :

$$\Delta U(k) = F(e(k), \Delta e(k)) \qquad (2)$$

Many types of membership function exist, in this paper, the Triangular-shaped functions shown in Figure (3), are chosen owing to their simplicity as well as the closer to human thinking

Fig.(3) The membership function

From the above, any controller can be implemented given the inputs and an output based on the proposed set of rules.

3 OPTIMAL FUZZY LOGIC SYSTEM

In this section, we develop an optimal fuzzy logic system, that is, it is optimal in the sense that it is capable of matching all the input-output pairs in the training set to any given accuracy. The basic idea of this optimal fuzzy logic system is described as :

For arbitrary $\varepsilon > 0$, there exists $\hat{\varepsilon} > 0$

$$\left|F(X^l) - g(y^l)\right| < \varepsilon \tag{3}$$

and

$$F(X) = \frac{\sum_{l=1}^{M} y_n^l \left(\prod_{i=1}^{n} \mu_{Fi}^l (X_i) \right)}{\sum_{l=1}^{M} \prod_{i=1}^{n} \mu_{Fi}^l (X_i)} \tag{4}$$

for all $l = 1,2,\ldots M$

where g ( ) is the desired output of the fuzzy logic system for input x(l), and f ( ) is the fuzzy logic system output, that is, we choose the number of rules in the optimal fuzzy logic system equal to the number of input-output pairs in the training set, with one rule responsible for matching one input-output pair $(x_1\ x_2\ , y)$. A fuzzy rule defines a fuzzy patch or subset of the input-output state-space of a system.It connects common sense knowledge with state - space geometry.

A fuzzy system can uniformly approximate any continuous function on a compact domain to any degree of accuracy. But the number of rule patches needed to cover a function's graph grows exponentionally with the number of input and output variables, the best ones cover the extrema in the function. This reduces much of optimal fuzzy function approximation to finding the zeroes of the derivative map. For mean-squared approximation, this result follows from the mean value theorem of caculus.

3.1 FUZZY BASIS FUNCTION

The most important advantage of the fuzzy basis function is that it provides a natural framework to combine both numerical information (in the form of input-output pairs) and linguistic information (in the form of fuzzy IF-THEN rules) in a uniform fashion. The fuzzy basis function (FBF) is defined as [7],

$$P_j(X) = \frac{\prod_{i=1}^{n} \mu_{Fi}^l (X_i)}{\sum_{j=1}^{M} \prod_{i=1}^{n} \mu_{Fi}^l (X_i)} \qquad j = 1,2,\cdots M \tag{5}$$

where $\mu_{Fi}(X_i)$ is the membership function, then the fuzzy logic system (4) is equivalent to an FBF expansion

$$f(X) = \sum_{i=1}^{M} P_j(X) \cdot \theta \tag{6}$$

where θ_j are constants.

The fuzzy logic system (4) can be analysed from two view points : First, if the parameters in the FBF as free design parameters, then the FBF expansion is nonlinear in the parameter. In order to specify, such FBF expansion, it must use nonlinear optimization input-output pair. Second, it is linear in the parameters θ_j, so the linear parameter search techniques could be applied.

Therefore , a conjugate gradient technique is applied in this paper to minimize the error in least square sense between the actual output y^l and the desired output d

Our goal is to use the FBF expansion as a controller to regulate the system to the origin from a certain range of initial conditions. The main objective is to design an FBF expansion f(X) such that the error between $f(X^o(t))$ and $d^o(t)$ is minimized.

3.2 THE PROCEDURE

In this section, a systematic method is given to help a designer get the best of reasoning algorithm that works well with the application required. An adaptive fuzzy logic system not only adjusts to time- or process-phased conditions but also changes the supporting system control, that is, an adaptive system modifies the characteristics of the rules , the topology of defuzzification based on predictive convergence. In order to describe. how the orthogonal least squares "OLS" learning algorithm works, consider a linear regression model

$$d(t) = \sum_{j=1}^{M} P_j(t) \cdot \theta_j + e(t) \tag{7}$$

where d(t) is system output, θ_j are real parameters. $p_j(t)$ are known as regressors,which are fixed functions of system inputs x(t), e(t) is the error signal, and N is number of input-output pairs (x,d)
In matrix form

$$d = P \cdot \theta + e \tag{8}$$

where $d = [d_1, \ldots, d_N]^T$, $p = [p_1, \cdots, p_M]$

with $p_i = [p_i(1), \cdots, p_i(N)]^T$,

$\theta = [\theta_1, \cdots, \theta_N]^T$,

and $e = [e(1), \ldots, e(N)]^T$

$$f = p \cdot \hat{\theta} + e \tag{9}$$

hence

$$f - d = p(\theta - \hat{\theta}) = p\varphi = \varphi^T \cdot \omega \tag{10}$$

The error function can be written as ;

$$e = f - d \tag{11}$$

where p is a positive definite matrix and θ is the parameter error function. Define the Lyapunov function candidate

$$V = \tfrac{1}{2} \varphi_k^T \cdot H \cdot \varphi_k \tag{12}$$

Then $\Delta V = \varphi_k^T \cdot H \cdot \Delta\varphi_k$ (13)

if we choose the adaptive law

$$\Delta\varphi = -\varphi_k^T \cdot e \cdot \omega = -e^2 \leq 0 \tag{14}$$

the system stability can be achieved, if

$$V = \sum \Delta V = -\varphi^T \cdot \omega \cdot H \cdot \omega^T \cdot \varphi = -\varphi^T \cdot \Omega \cdot \varphi \tag{15}$$

where $\Omega \rightarrow 0$ and $\varphi \rightarrow 0$ then $V \rightarrow 0$

it is an asymptotic stable system.

The proposed approach to develop a fuzzy logic control consists of five stages. For the given pairs

(x_1^i, x_2^i, y^i) where $f(x_1, x_2) \rightarrow y$

step 1:

Assume that,the range of each variable is known $[x_1, \hat{x}_1],[x_2, \hat{x}_2],[y, \hat{y}]$. Normalize each and find the corresponding scaling factor k_{x1}, k_{x2}, and k_y.

step 2:

Generate fuzzy rules from data pairs. Determine the degree of each x_1^i, x_2^i and y^i

step 3:

Assign a degree of each rule, the degree of this rule D(rule) is defined as

$$D(\text{rule}) = \mu_A(X_1)\cdot\mu_B(X_2) \quad (16)$$

step 4:

Create a combined fuzzy base by making a look-up table as shown in table 1

step 5:

Determine a mapping based on the combined fuzzy rule base

We use the following defuzzification strategy to determine, the output control y for given inputs (x_1, x_2)

$$\mu_{oi}^i = \mu_{I_1}^i(X_1)\cdot\mu_{I_2}^i(X_2) \quad (17)$$

Using rule i and O define the output region of rule i and I_1, I_2, the input region of the inputs X_1, X_2 respectively.

4 TEST CASE

The system considered in this study may be expressed as follows:

$$\dot{X}_1 = X_2 \quad , \quad \dot{X}_2 = f(\underline{X}) + u \quad (18)$$

where $f(\underline{X}) = \sin(\alpha\cdot X_1\cdot X_2)$

$\alpha = .01$, $\Delta t = 0.05$ seconds.

The step response of the proposed system is shown in figure (4).As it is clear, the system has a highly nonlinear response, F(X), due to its inherent characteristics. A fuzzy approximation is estimated to follow, to a great extent, such nonlinearity, D(X). On the same graph a plot for the error between the exact nonlinearity and the corresponding estimate. Based on this understanding, a feedback linearization is adopted to get a reliable linearized system.

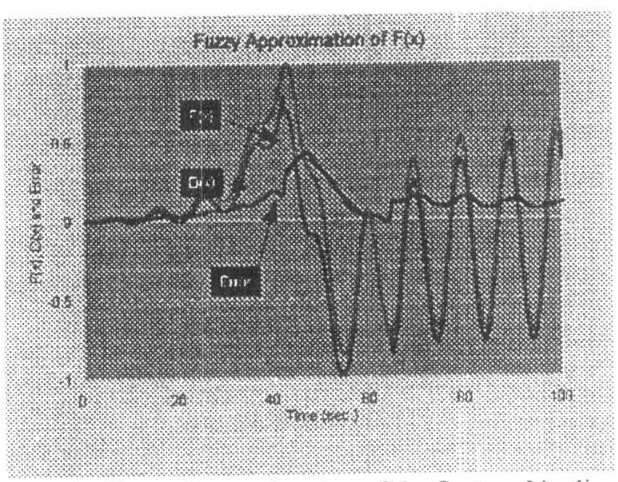

Fig. 4 - The Fuzzy Approximation of the System Nonlinearity

Fig. (5) shows the state variables in case of open loop operation which reflects instablity. The closed loop operation results in stabilising the system.

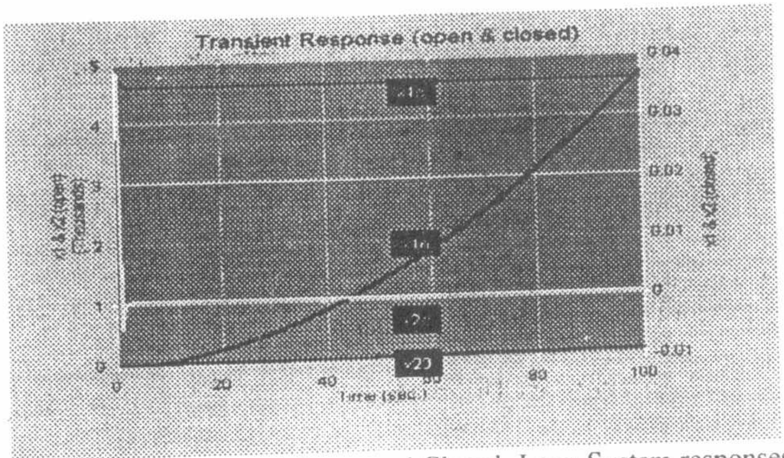

Fig. 5 - The Linearized Open- and Closed- Loop System responses.

From the above tests and analyses, it is concluded that the fuzzy-logic theory could be employed successfully to represent and estimate the nonlinear part of the system dynamics as a prior step to the feedback linearization for the purpose of obtaining a robust linear system.

5 CONCLUSION

This paper has introduced the application of conjugate gradient technique to control a highly nonlinear system. The fuzzy logic theory is introduced as a tool to generate an estimate value for the system nonlinearity. This estimate is employed in feedback linearization to result in a linearized system, that is valid for a wide range of operating conditions. A feedback is adopted to stablize the resulting unstable open loop linear system.

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