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Vibration Control of Flexible Nonlinear System using GA based Fuzzy Logic Controller

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Abstract

In the paper, Fuzzy Logic Controller(FLC) that determines its optimal coefficients using Genetic Algorithms is considered. It is also applied to the inverted pendulum problem known popularly as a standard plant. Flexibility of the inverted pendulum has been taken into account. In the results, Fuzzy Logic Controller under consideration successfully controls both rigid mode and flexible mode. The rule base of Fuzzy Logic Controller is automatically tuned using not only trial-error method but also Genetic Algorithms.

I. Introduction

Many studies have been performed to control the nonlinear dynamic systems using various techniques. They are used to model nonlinear control systems with uncertainty. In particular Fuzzy logic controller which is introduced by L. Zadeh[1], and practical application was done by Mamdani[2], which is a rule-based system pretending human experts with knowledge and experience. Abstract or subjective concepts can be represented with linguistic terms. Linguistic terms have been incorporated into rule-based systems to form fuzzy logic controllers(FLCs). FLCs are shown better performances than results of the conventional controllers in case of uncertain information to be acquired. In fact, the design of FLCs has often been a trial-and-error method in which most of the development time is devoted to the quest for efficient membership functions.

To solve these problems, many automatic design methods for systematic structures of FLCs have proved. Genetic algorithms which was introduced in 1970's are optimization search algorithms based on biological genetics and natural search[3]. The advantage of genetic algorithms is that they decrease to have local minimum in probabilistic using global search and don't need restrictions such as continuity of searching space and differentiability.

Takagi and Sugeno proposed to use the fuzzy controller(so called as TS fuzzy controller) whose consequent parts are described by linear equations[4]. TS fuzzy controller have been applied to many practical problems successfully. Because consequent parts of TS fuzzy controller is represented by linear equations of input variables, defuzzification is compact and it is easer to tune the consequents of the rules using many optimization techniques.

The inverted pendulum problem is popularly known as standard plant. Many papers have shown the inverted pendulum for demonstrating the success of various control methodologies[5]. To the best of authors knowledge, most of the study on inverted pendulum have considered system as a rigid one. However, in reality, flexibility must be taken into account in system analysis. In the paper, TS fuzzy controller using genetic algorithms for automatic tuning is used to the inverted pendulum with a flexible pole.

The remainder of the paper, section 2 reviews the TS fuzzy controller formulation and simple algorithms. Section 3 shows the structure of the controller under consideration and application on the problem. And some further discussions and

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the concluding remarks with the results are given in section 4.

II. Fuzzy Logic Controller and Genetic Algorithms

A. Takagi-Sugeno Fuzzy Controller

The pure fuzzy IF-THEN rules are of the following form :

$$R^{(l)}: \quad IF\ x_1\ is\ F_1^l \text{ and } \cdots \text{ and } x_n\ is\ F_n^l,$$
$$THEN\ y\ is\ G^l \qquad (1)$$
$$l = 1, 2, \ldots, M$$

where F_i^l and G^l are fuzzy sets, M is the number of the rules, and x_i and y are input, output linguistic variables. Instead of considering the fuzzy IF-THEN rules in the form (1), Takagi and Sugeno[4] proposed to use the following fuzzy IF-THEN rules:

$$R^{(l)}: \quad IF\ x_1\ is\ F_1^l \text{ and } \cdots \text{ and } x_n\ is\ F_n^l,$$
$$THEN\ y^l = c_0^l + c_1^l x_1 + \cdots + c_n^l x_n \qquad (2)$$
$$l = 1, 2, \ldots, M$$

where F_i^l is also a fuzzy set, c_i are real-valued parameters, and y is the system output due to rule. The final output of the TS fuzzy controller is computed as the weighted average of the output of rules in the rule base:

$$y(x) = \frac{\sum_{l=1}^{M} w^l y^l}{\sum_{l=1}^{M} w^l} \qquad (3)$$

where weight w^l is the degree of match of the premise parts.

$$w^l = \prod_{i=1}^{M} \mu_{F_i^l}(x_i) \qquad (4)$$

The main task in TS fuzzy controller design is to adjust the coefficients, c_i, to obtain the desired performance.

B. Genetic Algorithms

Genetic algorithms are optimization and machine learning algorithms. Their initial inspiration comes from the processes of natural evolution. The father of the theory is John Holland that explored algorithms, operating on strings of bits that he called chromosomes. This algorithms are simple, robust, and general; no knowledge of the search space is assumed[3].

Optimization is performed on a set of chromosomes, a population. Optimizing a population rather than a single individual contributes to the robustness of these algorithms. By maintaining a population of well-adaptive states based on the parallelism, the probability of trapping into a local minimum is greatly reduced. Populations evolve by selection (reproduction), crossover and mutation. Selection performs individual strings to be copied according to their relative object(fitness) values. Crossover recombines pair of chromosomes by swapping parts of them from a randomly selected point, to create two new string(offspring), and a change of the value in a string position is evolved by mutation. These algorithms use probabilistic rule to produce a new generation. this does not mean that they perform a completely random search.

Genetic algorithms generate a new generation $G(t+1)$ based on the previous one $G(t)$ as following[7]:

Step 1) $t = 0$
Step 2) Generate an initial population $G(t)$
Step 3) Evaluate $G(t)$
Step 4) If some termination conditions are met, go to Step 8)
Step 5) Generate a new generation $G(t+1)$ from $G(t)$
Step 6) Evaluate $G(t+1)$
Step 7) Return to Step 4)
Step 8) Stop

C. Description of the Inverted Pendulum with a Flexible Pole

In general the inverted pendulum system is composed of a rigid pole and a cart on which the pole is hinged. The control goal is to balance the pole starting from nonzero conditions by supplying appropriate force to the cart. In this paper the inverted pendulum however, is assumed that it has a flexible pole and a mass at the tip of the pole. The nonlinear model is obtained by Euler-Lagrange's method. The motion is model with one rigid body and one flexible mode. The figure of an inverted pendulum with a flexible pole is as following.

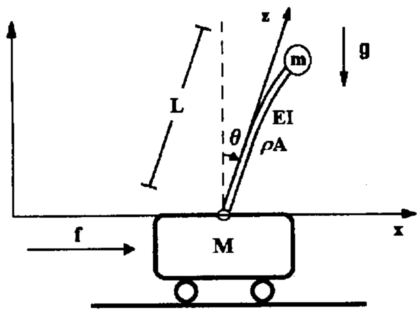

Fig. 1 Inverted Pendulum with a Flexible Pole

Where L is the length of the pole with ρA, EI, m and M is the mass of the tip and the cart, respectively.

From the vibration theory[6], let the displacement of a continuous pole be a form

$$w(z,t) = \Psi(z)\,v(t) \tag{5}$$

And for simplicity we select a function $\psi(z)$ as the first flexible mode[1)]

$$\Psi(z) = 4.5098z^2 - 3.4005z + 0.0009 \tag{6}$$

The used variables are in the following figure.

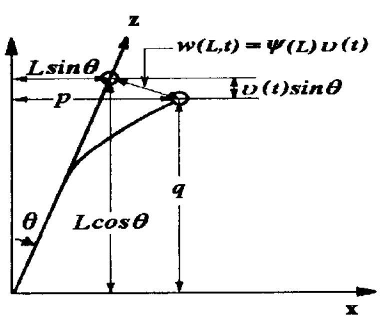

Fig. 2 Variables in the Inverted Pendulum with a Flexible Pole

1) The considered flexible pole has two boundary condition such as simply-supported end and free end. Then the original solution of the considered flexible pole is as following

$$\Psi(z) = 0.0197\sinh(3.9266z) - 0.7071\sin(3.9266z)$$

Using the Euler-Lagrange's method, we can obtain the dynamic equations of the inverted pendulum with a flexible pole.

$$\ddot{\theta} = \frac{Lg\sin\theta + gv\cos\theta - \{L\ddot{v} + 2v\dot{v}\dot{\theta} - \ddot{x}(L\cos\theta - v\sin\theta)\}}{L^2 + v^2}$$

$$\ddot{x} = \frac{f - \{m\dot{\theta}^2(L\sin\theta - v\cos\theta) - m\ddot{\theta}(L\cos\theta - v\sin\theta)\}}{m+M} - \frac{2m\dot{\theta}\dot{v}\sin\theta - m\ddot{v}\cos\theta}{m+M} \tag{8}$$

$$\ddot{v} = \frac{mv\dot{\theta}^2 + mg\sin\theta - m\ddot{x}\cos\theta - Lm\ddot{\theta} - \left(\frac{81.3532EI}{L^3}\right)v}{(m + 0.253984\rho AL)}$$

The used parameter of the inverted pendulum in the paper are as followings:
the gravity, g = 9.81[m/sec^2], mass of the cart, M = 1[kg], the tip mass, m = 0.2[kg], L = 0.5[m], EI = 1[kg/m^2], and ρA = 1[kg/m].

III. Fuzzy Logic Controller Synthesis and Results

Initially genetic algorithms generate a population of chromosomes. They provide the fuzzy rule-base the decoded chromosomes in the way of selecting the fittest value. The fitness function, J used in the study is given by:

$$J = \frac{1}{1 + \sum_{i=1}^{n}(\alpha e_\theta^2 + \beta e_v^2)} \tag{9}$$

where e_θ and e_v are the error of the angle θ and the displacement v, respectively. n is the total sampling number and α and β are constants. A schematic diagram of the fuzzy controller design method is shown in Fig. 3.

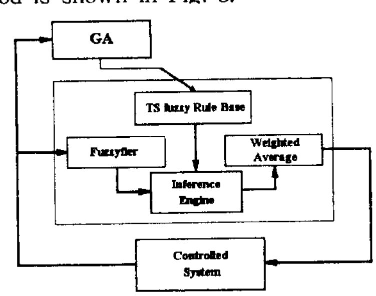

Fig. 3 Schematic diagram of the TS fuzzy controller

The considered TS fuzzy controller using genetic algorithms are applied to the inverted pendulum with a flexible pole. The objective is to control an angle of the pole as well as a displacement at the tip of the pole. The range for variables θ, $\dot{\theta}$, v and $\dot{v}$ are [-π/2, π/2]rad, [-5π/2, 5π/2]rad/sec, [-0.1, 0.1]m and [-0.5, 0.5] m/sec, respectively. 4 Membership functions used in the study are in Fig. 4. The TS fuzzy controller thus has 81 linguistic rules and 405(81 × 5) floating type parameters in consequent parts. The number of maximum generation is 50. The population size is fixed at 30. The probabilities of crossover and mutation are 0.5 and 0.1, respectively.

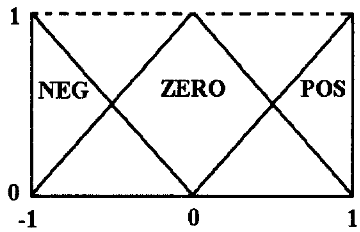

Fig. 4 Membership functions of 4 variables (θ, $\dot{\theta}$, v and $\dot{v}$)

Fig. 5 shows the angular response of the rigid body model and flexible body model of pole. Fig. 6 reveals the successful performance of FLC using genetic algorithms on the control of the nonlinear flexible system. The TS fuzzy controller using genetic algorithms is more efficiently. This technique generates very good control parameters even for a nonlinear flexible dynamic system.

IV. Discussions and Conclusion

A technique is discussed in which genetic algorithms are used to design TS fuzzy controller for a nonlinear flexible dynamic system such as the inverted pendulum with a flexible pole. The structure of the TS fuzzy controller is represented. The TS fuzzy controller combines with genetic algorithms. Next, TS fuzzy controller using genetic algorithm for automatic tuning is applied to control the flexible inverted pendulum.

Genetic algorithms improve the performance of the TS fuzzy controller. Because of these, it is concluded that genetic algorithms are efficient and a powerful tool in implementing fuzzy logic controller. As seen from the result in Fig. 6, GA based FLC successfully control the tip motion of flexible pole in much shorter settling time. This means the GA based FLC technique is appropriate even for the control of nonlinear flexible system.

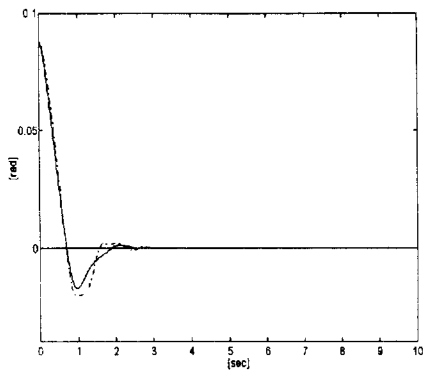

Fig. 5 angle of the pole

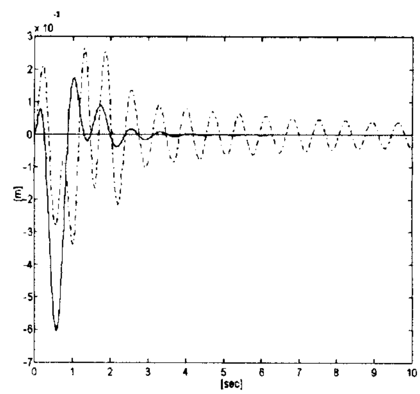

Fig. 6 displacement of the tip

········· : for rigid mode only
——— : for rigid and flexible mode

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