DESIGN OF A HYBRID FUZZY LOGIC CONTROLLER FOR A SINGLE LINK FLEXIBLE MANIPULATOR WITH GENETIC ALGORITHMS

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Abstract: To reduce end point vibration of a single-link flexible manipulator without sacrificing its speed of response is a very challenging problem since the faster the motion, the larger the level of vibration. A conventional controller can hardly meet these two conflicting objectives simultaneously. This paper presents a genetic algorithm (GA) based hybrid fuzzy logic control strategy to achieve that goal. A proportional-derivative (PD) type fuzzy logic controller utilising hub-angle error and hub-velocity feedback is designed for input tracking of the system. GA is used to extract and optimise the rule base of the fuzzy logic controller. The fitness function of GA process is formed by taking weighted sum of multiple objectives to trade off between system overshoot and rise time. Moreover, scaling factors of the fuzzy controller are tuned with GA to improve its performance. A GA-based multimodal command shaper is then designed and augmented with fuzzy logic controller to reduce the end-point vibration of the system. The performance of the hybrid control scheme is assessed in terms of input tracking capability and vibration suppression at the end-point. A significant amount of vibration reduction has been obtained at the end-point, especially at the first three resonance modes of the rig structure with satisfactory level of overshoot, rise time, settling time and steady state error. Copyright © 2002 USTARTH

Keywords: command shaper, flexible manipulator, fuzzy logic control, genetic algorithm.

1. INTRODUCTION

Flexible manipulators are lighter, faster and less expensive than rigid ones but they pose various challenges in research as compared to rigid manipulators, ranging from system design, structural optimization, and control. Positioning is a fundamental function of flexible manipulators. A number of methods have been attempted to improve the response time and to control the system vibration (Cannon and Schmitz, 1884; Singer and Seering, 1990; Tokhi and Azad, 1997; Mohammad and Tokhi, 2002; Romeo et al., 2002; Jinfene and Andrews, 2005). The objective of this work is to develop a hybrid fuzzy logic control strategy based on genetic algorithm (GA) (Holland, 1975; Goldberg, 1989) whereby a flexible robotic arm is moved from one position to another in the least amount of time with minimum vibration. It is difficult to find a suitable solution through analytical means meeting these two objectives simultaneously. So, GAs with different types of objective functions and their sum of weighted values are used to find an effective solution that trades-off between these conflicting features. Firstly, a GA based automated design of the fuzzy rule base is presented. Moreover input and output scaling factors are tuned to minimise overshoot and rise time of the system’s response. Secondly, a GA based multimodal command shaper (Tokhi et. al., 2005) is designed to reduce vibration at the end point and augmented as a feedforward component with the fuzzy controlled closed loop system.

2. EXPERIMENTAL SET-UP

In this study, an aluminium type single-link flexible manipulator of dimensions 900×19.008×3.2004 mm3, Young’s modulus, $E = 71 \times 10^8$ N/m², area moment of inertia, $I = 5.253 \times 10^{-11}$ m⁴, mass density per unit volume, $\rho = 2710$ kg/m³, and hub inertia, $I_H = 5.8598 \times 10^{-4}$ kgm², is considered (Tokhi and Azad, 1997). Figure 1 shows the schematic diagram of the single-link flexible manipulator system, where $X_0OY_o$ and $XOY$ represent the stationary and moving co-ordinates respectively, $\tau$ represents the applied torque at the hub. A dynamic state-space model of the flexible manipulator is derived using the finite element (FE) method and used in this work where motion is confined to the $X_0OY_o$ plane only.

Fuzzy logic control (FLC) has been successfully applied in the control of various physical processes (Zadeh, 1965, 1973; Mamdani, 1974). A proportional-derivative (PD) type fuzzy logic controller (FLC) utilising hub-angle error and hub-velocity feedback is developed to control the rigid-body motion.
of the system (Siddique and Tokhi, 1999). A GA-based multimodal command shaper (CS) is then incorporated to reduce the end-point acceleration of the system (Alam et al., 2004; Tokhi et al., 2005). The hybrid fuzzy controller proposed in this work is shown in Figure 2 where $\theta$ and $\dot{\theta}$ are hub angle and hub velocity of the flexible manipulator whereas $k_1$, $k_2$ and $k_3$ are scaling factors for two inputs and one output of the FLC used with the normalised universe of discourse for the fuzzy membership functions.

Triangular membership functions are chosen for inputs and output (see Figure 3). To construct a rule base, the hub angle error, hub velocity and torque input are partitioned into five primary fuzzy sets as

- Hub angle error $E = \{NB, NS, ZO, PS, PB\}$
- Hub Velocity $V = \{NB, NS, ZO, PS, PB\}$
- Torque $U = \{NB, NS, ZO, PS, PB\}$

where $E$, $V$ and $U$ are the universes of discourse for hub angle error, hub velocity and torque input respectively. The $n$th rule of the rule base for the FLC, with error and change of error as inputs, is as, $R_n$: IF (e is $E_i$) AND (v is $V_j$) THEN (u is $U_k$), $n = 1, 2, ..., N_{max}$ is the $n$th fuzzy rule, $E_i$, $V_j$, and $U_k$, for $i, j, k = 1, 2, ..., 5$ are the primary fuzzy sets. The rule base is shown in Figure 4.

4. COMMAND SHAPING FOR VIBRATION CONTROL

Since its introduction (Singer, and Seering, 1990; Singhose et al., 1995) the method of command shaping has been applied to the control of different types of flexible systems Mohammad and Tokhi, 2002; Romeo et al., 2002). The design rules result in the amplitudes ($A_i$) and time locations ($t_i$) for a 2-impulse sequence as (Singhose et al., 1995)

$$t_1 = 0, \quad t_2 = \frac{\pi}{\omega_d}, \quad t_3 = \frac{2\pi}{\omega_d},$$

$$A_1 = \frac{1}{1+2K+K^2}, \quad A_2 = \frac{K}{1+2K+K^2},$$

$$A_3 = \frac{K^2}{1+2K+K^2}$$

where, $K = e^{-\eta \omega_d / \sqrt{1-\xi^2}}$, $\omega_d = \omega_n \sqrt{1-\xi^2}$, $\omega_n$ is the natural frequency and $\zeta$ is the damping ratio of the system. Higher impulse command shapers are designed with the view to increase robustness to errors in natural frequencies of the system. The time locations and amplitudes of 3-impulse and 4-impulse command shaper are as follows:

5. GENETIC ALGORITHMS

GA as a stochastic optimization algorithm is motivated by the mechanisms of natural selection and evolutionary genetics (Holland, 1975; Goldberg, 1989). The basic element processed by a GA is a string formed by concatenating sub-strings, each of which is a numeric coding of a parameter. Each string represents a point in the search space. The Selection, Crossover and Mutation are the main operations of GA. Selection direct the search of GA toward the best individual. Crossover can cause to exchange the properties of any two chromosomes via random decision in the mating pool. Mutation is a random alternation of a bit in the string and assists in keeping delivery in the population.
5.1 GA based fuzzy logic controller

GA has been used to design and optimise different parameters of fuzzy controllers, like, membership functions, rule base and scaling factors (Karr, 1991; Herrera et al., 1995; Carse et al., 1996; Ishibuchi et al., 1997).

Chromosome representation of rule base: In this work, GA is used to extract and optimise the rule-base of a PD-like FLC for input tracking control of the flexible manipulator. The PD-like FLC has two inputs and one output. The linguistic variables can be represented by integer values, for 1 for NB, 2 for NS, 3 for ZO, 4 for PS and 5 for PB. Applying this code to the fuzzy rule-base represented in Figure 4, the encoded rule-base shown in Figure 5 is obtained. A chromosome is thus obtained from the decision table by going row-wise and coding each output fuzzy set as an integer in \( \{1,2,\ldots,n\} \), where \( n \) is the maximum number used to label the membership functions defined for the output variable of the FLC. In this case, \( n = 5 \) as shown in Figure 5.

<table>
<thead>
<tr>
<th>Hub angle</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>1</td>
</tr>
<tr>
<td>NS</td>
<td>2</td>
</tr>
<tr>
<td>ZO</td>
<td>3</td>
</tr>
<tr>
<td>PS</td>
<td>4</td>
</tr>
<tr>
<td>PB</td>
<td>5</td>
</tr>
</tbody>
</table>

![Fig. 5. Chromosome representation of rule base](image)

Encoding Scheme: Figure 6 shows the encoding scheme of the fuzzy rule base whereas Figure 7 shows the relationship between encoded chromosome and it’s corresponding linguistic rule. Binary GA with fixed length chromosome is used in the automated rule generation process for two inputs and one output PD-like FLC. Triangular membership functions of five linguistic variables are used for both inputs and output which can be represented by integer numbers from 1 to 5 as indicated in Figure 5. Three bits Gray codes are used to represent each linguistic variable. For each rule 4 binary strings each of 3 binary bits. Randomly generated binary bits can be represented by integer numbers, for 1 for NB, 2 for NS, 3 for ZO, 4 for PS and 5 for PB. Applying this code to the fuzzy rule-base represented in Figure 4, the encoded rule-base shown in Figure 5 is obtained. A chromosome is thus obtained from the decision table by going row-wise and coding each output fuzzy set as an integer in \( \{1,2,\ldots,n\} \), where \( n \) is the maximum number used to label the membership functions defined for the output variable of the FLC. In this case, \( n = 5 \) as shown in Figure 5.

![Fig. 6. Encoding Scheme of fuzzy rule base](image)

![Fig. 7. Chromosome Vs linguistic rule](image)

<table>
<thead>
<tr>
<th>Linguistic rule</th>
<th>Effective</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF (e is NS) OR (v is PS) THEN (u is NS)</td>
<td>Not effective</td>
</tr>
</tbody>
</table>

Objective function is as follows:

\[
\text{Objective function} = w_1 f_1(x) + w_2 f_2(x),
\]

where \( f_1(x) \) represents normalised absolute sum of tracking error and \( f_2(x) \) normalised system overshoot. Elitism technique is used throughout the optimisation process which allows preserving the best solution of each generation. The optimisation process was run for a maximum generation of 80 and yielded an FLC with 12 rules in the rule-base which was quite small and effective for controlling the manipulator. The effective 12 linguistic rules are displayed in Figure 8.

5.2 GA based command shaper

The command shaping method involves convolving a desired command with a sequence of impulses (Singer, and Seering, 1990; Singhose et al., 1995). The design objectives are to determine the amplitudes and time locations of the impulses based on the natural frequencies and damping ratios of the system. From the frequency domain representation of the open loop end-point response (Figure 14) it is evident that, within the range of frequencies shown, the system has three resonance modes approximately at 13Hz, 35Hz and 65Hz respectively which cause most of the vibration while in operation. It is difficult to find out the corresponding damping ratios associated with those resonance modes by analytical means. Moreover, in the proposed control strategy, the command shaper would be augmented with the FLC based closed-loop system. The dynamics of the closed-loop system would
definitely vary compared to the open-loop system which will further be difficult to analyse. Without this prior knowledge of the system, the standard equations (1), (2) and (3) cannot be used to design an effective command shaper. From the open-loop response, it is generally assumed that multi-modal (3-modes) might be suitable for the system to reduce vibration at end-point. For multi-modal command shaper, an impulse sequence for each vibration mode can be designed independently.

1. if (error is NS) or (velocity is NS) then (output is ZO)
2. if (error is NB) or (velocity is PS) then (output is ZO)
3. if (error is NS) or (velocity is NS) then (output is PB)
4. if (error is PS) or (velocity is NB) then (output is ZO)
5. if (error is NS) or (velocity is NB) then (output is PB)
6. if (error is PB) or (velocity is PB) then (output is NB)
7. if (error is PB) or (velocity is PS) then (output is NS)
8. if (error is PS) or (velocity is NB) then (output is ZS)
9. if (error is ZO) or (velocity is NS) then (output is ZO)
10. if (error is NS) or (velocity is NB) then (output is PB)
11. if (error is PS) or (velocity is PB) then (output is NB)
12. if (error is NB) or (velocity is NS) then (output is ZO)

Fig. 8. Linguistic rules of optimised FLC

In this work, GA is used to determine the amplitudes and time locations of the impulses of multi-modal (3-mode) command shaper (Alam et al., 2004; Tokhi et al., 2005). The objective function of the GA-based design procedure is chosen as the integral of absolute value of the signal recorded at the end-point;

Objective function, \[ IAE = \int_0^T |y_{ep}(t)| dt \] (4)

where \( y_{ep}(t) \) represents the signal at the end point of the flexible manipulator.

6. IMPLEMENTATION

The GA optimisation process is initialised with a random population consisting of 50 individuals. The population is represented by binary strings each of 20 bits, called chromosome. Each chromosome consists of six separate strings constituting three terms for amplitudes and another three for time locations corresponding to three-mode command shaper. These random binary strings are converted into real values within a defined range that ensures stability.

The first three values of the first rows are termed as K1, K2 and K3, and are used to calculate the impulses of three sequences according to equation (1) (for 2 impulse command shaper). The next three random values of the same row are used to calculate the time locations of the corresponding sequences. Equation (1) is used with random values of K in view of maintaining the same magnitude ratios among the impulses as provided by the theoretical method.

Three separate impulse sequences are thus formed with the values of the first row of the randomly generated initial population. These impulse sequences are convolved with each other to form a final sequence which is later convolved with the input finite pulse signal to form the shaped input. This signal is applied to the system, designed in Simulink, as shown in Figure

7. RESULTS AND DISCUSSION

Firstly a PD-like FLC was design with 25 rules as a closed-loop component of the hybrid control strategy for input tracking of the flexible manipulator. The rule base was extracted based on trial and error and three scaling factors were chosen heuristically. This PD-like FLC with 25 rules is termed as Case-1 in the following discussion. Table 1 shows the performance measures of different control strategies in the time domain. For Case-1, overshoot, rise time, settling time and steady state error were recorded as 7.2397%, 0.4462 sec, 1.2392 sec and 0 respectively while the mean squared value of signal at end point was 3.0727.

In the next step, GA was utilised to extract and optimise the rule base of FLC in the same application. A reduced rule base (12 rules) FLC was obtained with more than 50% reduction in terms of number of rules compared to Case-1 but it produced higher overshoot (14.5067%) in system’s response. This reduced rule based FLC, indicated as Case-2, recorded some reduction in terms of rise time and settling time compared to
Case-1. In order to reduce the overshoot, three scaling factors of FLC, \(k_1\), \(k_2\) and \(k_3\) were tuned with GA. The resultant controller (Case-3) completely eliminated the overshoot (0%) with satisfactory level of rise time (0.3654 sec) and settling time (0.5496) as shown in Table 1 achieved. The hub angle responses of Case-1, Case-2 and Case-3 are shown in Figure 11. Figures 12 shows the end-point acceleration for open loop, Case-1 and Case-3 in the time domain. For closed-loop control strategies (Case-1 and Case-3) the level of vibration is much smaller compared to open-loop response.

In the next step, GA based multi-modal command shaper was designed and augmented with the optimised and retuned (scaling factors) FLC. This augmentation results a hybrid control strategy which is aimed to reduce vibration at the end-point as well as to follow the reference input without much deviation. Three different types of multi-modal command shapers, namely, 2-impulse, 3-impulse and 4-impulse, were designed and augmented with the FLC. Case-4, Case-5 and Case-6 represent hybrid fuzzy controllers with 2-impulse, 3-impulse and 4-impulse command shapers respectively. Table 2 shows the performance measures of different control strategies. The inclusion of command shaper in a control scheme always causes delay in the system response which in turn results longer settling time. The delay in response or the rise time increases with the number of impulses in the command shaper. The rise times for Case-4, Case-5 and Case-6 were 0.3662, 0.3666 and 0.3672 sec. respectively.

### Table 1 Performance measures in time domain

<table>
<thead>
<tr>
<th>Control Strategy</th>
<th>Overshoot (%)</th>
<th>Rise time (Sec)</th>
<th>Settling time (Sec)</th>
<th>Steady state error</th>
<th>End point acceleration (Mean squared value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-1</td>
<td>7.2397</td>
<td>0.4462</td>
<td>1.2392</td>
<td>0</td>
<td>3.0727</td>
</tr>
<tr>
<td>Case-2</td>
<td>14.5067</td>
<td>0.3070</td>
<td>0.9866</td>
<td>0</td>
<td>2.6361</td>
</tr>
<tr>
<td>Case-3</td>
<td>0</td>
<td>0.3654</td>
<td>0.5496</td>
<td>0</td>
<td>1.7305</td>
</tr>
</tbody>
</table>

Case-1: PD-like Fuzzy controller (25 rules)
Case-2: FLC with GA optimised rule-base (12 rules)
Case-3: FLC with GA optimised rule-base (12 rules) and input-output scaling factors

Moreover, the system response with all the control strategies involving command shaper were slower than that in Case-3 (0.3654 sec), which is FLC without command shaper. Similar behaviour was observed in case of settling time which is minimum for Case-3 and maximum for Case-6.

It is evident from Table 2 that, all the control strategies (Case-4, Case-5 and Case-6) involving command shaper reduced vibration at the end-point quite significantly compared to the FLC alone (Case-3). The mean squared values of signals at end-point were 1.7305, 0.2201, 0.1449 and 0.1079 for Case-3, Case-4, Case-5 and Case-6 respectively. Case-6 produced the best result in terms of vibration reduction at the end point, followed by Case-5 and Case-4. End-point response for different control strategies is shown in Figure 13. The frequency domain response of end-point vibration, see Figure 14, for different control strategies indicates the effectiveness of command shaper in the hybrid control strategy proposed here. The multi-modal command shaper significantly reduced vibration at the first three resonance modes, which cause most of the vibration in the test rig. It is clear from Figure 22 that the amount of reduction is much higher at mode-2 (33Hz) and mode-3 (65Hz) compared to mode-1 (13Hz).
8. CONCLUSION

A GA based hybrid fuzzy logic control strategy has been developed for input tracking and vibration reduction at end-point of a single-link flexible manipulator. Multi-objective GA with weighted sum approach has been used to extract and optimise the rule base of the FLC. The resulting reduced rule base may prove very significant in terms of computational complexity, memory requirements and processing time. Although the optimised FLC has performed well in input tracking with satisfactory level of overshoot, rise time, settling time and steady-state error but cannot reduce vibration at the end point to a satisfactory level.

To reduce vibration at end-point, a GA based multi-modal command shaper has been designed and augmented with FLC. It has been observed that the vibration is reduced significantly at the cost of very small amount of delay due to the inclusion of the command shaper. A GA based multi-modal command shaping technique has been proved to be very effective for vibration reduction where prior information about natural frequencies and damping ratios of a system may not be available. All the results show that the hybrid fuzzy control system has performed well with good tracking performance and significant reduction in vibration at end-point.

REFERENCES


