Hybrid Control Method for a Flexible Manipulator

Run-Min Hou, Da Hu, Qiang Gao, Ming-Ming Lv

Department of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, China
E-mails: 187189579@qq.com

Abstract. This paper proposes an inverse adaptive network based fuzzy inference system (ANFIS) to control the nonlinearity, wide variations in loads, and uncertain disturbance of a single-link flexible robot manipulator. To reduce the end-point vibration of a single-link flexible manipulator without sacrificing its speed of response is a very important problem as the motion become faster. An inverse-ANFIS with feedback and feed-forward method is used to optimize parameters of the controller for flexible dynamic of the systems. The system performance with the controllers is presented and analyzed in the time and frequency domains. Moreover, it concentrates on the system from input torque to hub-angle, hub-velocity and end-point acceleration outputs. The results of the simulation test prove that the proposed are effective and suitable.

1. Introduction
The flexible manipulator systems are often used in the industrial. There supply several advantages with flexible manipulators which include high motion speed, light weight, reduced cost for mechanical, lower energy cost, safety due to eliminated force, low mounting requirement and easy to design. However, the control of flexible manipulators to maintain accurate positioning is an extremely important problem. Due to the flexible nature and distributed characteristics of the system, the dynamics are highly non-linear and complex. Problems arise due to precise positioning requirement, vibration due to system flexibility, difficulty in obtaining accurate model of the system and non-minimum phase characteristics [1, 2]. In order to solve these problems, it is necessary to use effective methods to control the manipulator’s response.

The control strategies for flexible robot manipulator systems can be classified as feed-forward and feed-back. A feed-forward control scheme introduced by Lou who has created considerable interest among the researchers [3]. Li et al introduces that the method has been applied to the control of different types of systems for vibration reduction or trajectory tracking [4]. Alam et al presented an open-loop control strategy for vibration suppression of a flexible manipulator system where low-pass and band-stop filtered bang–bang torque inputs were developed on the basis of the identified vibration modes and applied to the system [5]. However, designing an effective command shaper requires a priori knowledge of the system characteristic parameters, such as resonance frequencies and corresponding damping ratios, to produce a command that results in zero residual vibration. On the other hand, Feedback controllers can be designed to be robust to parameter uncertainty. For flexible manipulators, feed-forward and feedback control techniques are used for vibration suppression and position control, respectively. An acceptable system performance without vibration that accounts for system changes can be achieved by developing a hybrid controller consisting of both control
techniques [6]. Thus, a properly designed feed-forward controller is required, with which the complexity of the required feedback controller can be reduced.

In some literatures, lots of studies are available related to the design of controller for a flexible manipulators employing PID, adaptive neural network, artificial intelligence and adaptive fuzzy logic algorithms [7, 8]. [9] proposed the practical implementation of intelligent PID tracking controller on a single flexible link. Jang [10] proposed an adaptive neural-fuzzy inference system (ANFIS), in which a polynomial is used as the defuzzifier. It distinguished itself from normal fuzzy logic systems by the adaptive parameters. In this paper, an inverse-ANFIS is studied as a complement to conventional feed-forward and feed-back control, and the effectiveness of the resulting scheme is assessed in input tracking and vibration reduction of a flexible robot manipulator.

This paper has been divided into five sections; first part is introducing the flexible manipulator and review the exits acknowledgement. The second section is to describe the structure of the experimental flexible manipulator. The third part is describing implementation of the control strategies. The fourth part is simulation result and comparison. The final part is conclusion of this work.

2. The Flexible Manipulator System

A single-link flexible manipulator is shown in figure 1 where \(E, P, I, M_p\) and \(I_h\) presents Young’s modulus, system mass density, area instant of inertia, system payload and hub inertia, respectively. The measurement devices include a shaft encoder with a resolution of 2048 pulses to measurement of hub angle for the manipulator; a tachometer is measured for hub velocity of the manipulator and an accelerometer at the end-point is used to measurement at end-point acceleration of the manipulator, respectively.

Figure 1. The simpler manipulator

In this paper, the characteristic parameters of the manipulator arm are shown below:

1. Hub inertia is \(5.85 \times 10^{-4} \text{kgm}^2\);
2. Young’s modulus is \(71 \times 10^8 \text{N} / \text{m}^2\); and Second moment of inertia is \(2.0129 \times 10^{-11} \text{kg} / \text{m}^2\).

In the flexible manipulator, using matrix formulation, the equation can be written as:

\[
Y_{i,k+1} = A Y_{i,k} + B Y_{i,k-1} + C F
\]

\[
Y_{i,k+1} = \begin{pmatrix} Y_{i,k} \\ Y_{n,k} \end{pmatrix}; \quad Y_{i,k} = \begin{pmatrix} Y_{i,k} \\ Y_{n,k} \end{pmatrix}; \quad Y_{i,k-1} = \begin{pmatrix} Y_{i,k-1} \\ Y_{n,k-1} \end{pmatrix};
\]

Where, \(Y_{i,k+1}\) is the substitution of the manipulator points at step time \(k + 1\). \(Y_{i,k}\) and \(Y_{i,k-1}\) are substitution at time steps \(k\) and \(k-1\), respectively.

A is an \(n \times n\) matrix whose completely according on the flexible manipulator definition and B is an \(n \times n\) matrix divided into the number of sections the manipulator, C is a constant matrix and F is an \(n \times 1\) matrix.

A state-space formulation of the manipulator can be calculated according to the matrix formulation. Moreover, depend on the notation for simulation of discrete-time linear systems, the equations of the flexible manipulator can be shown as:
\[ x(n + 1) = Gx(n) + Hu \]  \tag{3} \\
\[ y(n) = Wx(n) + Su \]  \tag{4}

where

\[ G = \begin{bmatrix} A & B \\ 1 & 0 \end{bmatrix}; \quad W = [1, 0, \ldots, 0] ; \quad S = [0, 2, \ldots, 0] ; \quad H = \begin{bmatrix} C \\ 0 \end{bmatrix} ; \]

\[ u = [1, 0, 0, \ldots, 0]^T. \]

And N shows the number of sections.

3. Methodology

3.1. ANFIS Control Method

Adaptive network based fuzzy interference system is implemented a fuzzy interference system based on adaptive network. It allows one to construct a fuzzy interference system from a given data set. Thus the ANFIS combines all possible benefits of neural network and fuzzy logic [11]. In this paper, the Type III ANFIS is discussed. The figure 2 shows five-layer network ANFIS structure.

The ANFIS is combined with two parts. The first part is the antecedent and the second is the conclusion part, which are based in network architecture with each other fuzzy rules.

As the figure shown, the five layers equivalent ANFIS has two input and one output. In the each same layer, it has same functions as described below [12]:

The first layer runs a fuzzification process. Every node in this layer can be described with node function is shown as:

\[ G_i = \mu A_i(x) \]  \tag{5}

Where, \( i \) is each node, \( x \) is the input to the node \( i \), \( A_i \) relates with this node function and \( G_i \) is a membership function (MF) of \( A_i \) . Due to the bell function has more than one parameter MF, it can solve a non-fuzzy set, moreover it can make the trajectory smoothness and concise at all the points. Thus, chosen bell function as ANFIS membership function in this paper. The bell-shaped with minimum equal to zero and maximum equal to 1, such as:

\[ \mu A_i(x) = \frac{1}{1 + \left(\frac{x - c_i}{a_i}\right)^2b_i} \]  \tag{6}

or

\[ \mu A_i(x) = \exp\left\{-\left(\frac{x - c_i}{a_i}\right)^2\right\} \]  \tag{7}

where \( a_i, b_i \) and \( c_i \) is a membership function parameter set.

The second layer executes previous part of the fuzzy rules.
\[ \omega_i = \mu A_i(x) \times \mu B_i(x), i = 1, 2 \]  

The third layer normalizes the membership functions.

\[ \bar{\omega}_i = \frac{\omega_i}{\omega_i + \omega_2}, i = 1, 2 \]  

In the fourth layer, every node in this layer is based on node function such as:

\[ G^4_i = \bar{\omega}_i f_i = \bar{\omega}_i (p_i x + q_i y + r_i) \]  

Where, \( \bar{\omega}_i \) is output of layer 3, and \( p_i, q_i \) and \( r_i \) is parameter set.

The last layer calculates the output of the fuzzy system as the summation of all signals of layer four.

\[ G^5 = \sum_i \bar{\omega}_i f_i = \sum_i \frac{\omega_i f_i}{\omega_i + \omega_2} \]  

Form the figure 2, the output \( f \) can be rewritten as:

\[ \begin{cases} f_1 = p_1 x + q_1 y + r_1 \\ f_2 = p_2 x + q_2 y + r_2 \end{cases} \Rightarrow \frac{\omega_1 f_1 + \omega_2 f_2}{\omega_1 + \omega_2} = \bar{\omega}_1 f_1 + \bar{\omega}_2 f_2 \]  

**3.2. Training Procedure**

Following to the development of ANFIS method, some algorithms have been submitted as learning rules. There have four methods to update the parameters, as listed below depending on their computation complexities:

1. Gradient Descent Only: all parameters are updated by the GD
2. GD and one pass of LSE: the LSE is executed only once at the very beginning to get the initial values of the conclusion parameters and then the GD replaces to update all parameters.
3. All parameters can be updated with using extended Kalman filter method.

In this paper, the simulation algorithm is performance by using hybrid method which includes the gradient descent and the least squares estimate to update parameters. Moreover, the inverse-ANFIS is used as a nonlinear modeling approach to instead with using ANFIS, the ANFIS becomes to inverse-ANFIS by shifting input to output.

**4. Simulation Result and Analysis**

In this paper, the single flexible manipulator simulation results shows the control simulation result with using PID and inverse ANFIS for feed-forward and feedback in time domain and frequency domain. Usually choose approximately frequency at 11Hz, 35Hz, and 65Hz to dominant the flexible of manipulator for the first three modes of flexible manipulator.

Simulation results of the response of the single-flexible manipulator system with using inverse ANFIS for feed-forward and feed-back controller algorithm is presented in this part. In order to test and verify the effectiveness of the inverse ANFIS control, the close loop without tune, PID-PID and PID with inverse-ANFIS controller are been used to compare it.

Due to the non-linear dynamic system, the plant is generally uncertain, thus it is essentially to select parameters of the controller in order to create a successfully inverse ANFIS plant. The table 1 shows good parameters chosen for creating inverse-ANFIS mode.

Table 1. The ANFIS parameter select for feed forward and feedback

| Inverse-ANFIS      | Input MF | Input MF type | Output MF | Data select | Epochs |
|---------------------|----------|---------------|-----------|-------------|--------|
| HA feed-forward     | 7        | bell- function| Linear    | 8505        | 4      |
| EPA feedback        | 5        | bell- function| Linear    | 7555        | 4      |
The performance of the inverse ANIFS controller in hub angle response and in suppressing the vibration of the flexible manipulator without inertia, payload and no damping in frequency domain are shown in figure 3-figure 4.

The figure 3 and figure 4 shows the hub angle response and suspension of vibration at end-point acceleration in frequency domain respectively, where the blue solid line is reference input, the black dotted-line shows the close-loop without controller, the purple solid line represents PID-PID controller, and the green dotted-line graph the inverse-ANFIS. It is noted that the inverse ANFIS system tracked the demanded hub-angle well as compared to PID-PID and without tune for hub-angle control. Moreover, the inverse ANFIS is close vicinity of tracing the trajectory at the second duration more than others.

![Figure 3. Comparison hub-angle response for each controller](image)

The comparison results with use close loop without tune, PID-PID, inverse-ANFIS controller schemes are validated in this section. It is shown that the PID-PID, inverse ANFIS and closed-loop without controller for feed-forward and feedback gave the manipulator steady-states response of, 82.53°, 80.53° and 73.17°, respectively.

The inverse-ANFIS gave the minimum no overshoot, whereas the PID-PID controller gave 5.9378% overshoot. Although the close-loop without tune can gave the zero overshoot, but the steady-state output of 73.17°. The setting time for without tuning, PID-PID and inverse-ANFIS was 3.3535s, 2.8918s and 2.6432s, respectively.

![Figure 4. Comparison EPA responses for each controller in frequency domain](image)

The table 2 shows the power spectrum density test compare with close-loop without tune, PID-PID and inverse ANFIS controllers at end point acceleration. All controllers gave the same frequency at 11.01Hz, 35Hz and 65Hz, respectively.
Table 2. EPA resonance frequency and magnitude for each controller

| Magnitude EPA (deg/Hz) | 11.01Hz | 35Hz | 65Hz |
|-----------------------|---------|------|------|
| PID-PID               | 26.24   | 0.695| 0.03585 |
| Inverse ANFIS         | 16.81   | 0.364| 0.02959 |
| uncontrolled          | 26.24   | 0.695| 0.0305 |

5. Conclusion
In paper, the development of advanced controllers along with an inverse ANFIS model controller for reducing vibration during the dynamic model has been presented and verified within a single flexible manipulator system. Vibration reduction at end-point acceleration and perform position at hub-angle with PID-PID controller is shown well comparable to that achieved with inverse ANFIS controller. The aim of modeling and control have been finished very well.

References
[1] W. Belhaj, O. Boubaker, On MIMO PID control of the Quadruple-tank process via ILMI approaches : Minimum and non-minimum phase system case studies, 10th International IFAC Symposium on Dynamics and Control of Process Systems, (12) 2013, 481- 486.
[2] B.S Reddy, A. Ghosal, “Nonlinear Dynamics of a Rotating Flexible Link”, Journal of Computational and Nonlinear Dynamics, vol. 10, no 6, 2015, 061014, 1-8.
[3] J.Q. Lou, Y.D. Wei, G.P. Li, and et al, “Optimal Trajectory Planning and Linear Velocity Feedback Control of a Flexible Piezoelectric Manipulator for Vibration Suppression”, Shock and Vibration, 952708, 2015, 1-11.
[4] Li Erchao, Li Zhanming and He Junxue, “Robotic Adaptive Impedance Control Based on Visual Guidance”, International Journal on Smart Sensing and Intelligent Systems vol. 8, no 6, 2015, 2159-2174.
[5] M.S Alam, M.O Tokhi, A.J Chipperfield, and et al. “Designing feedforward command shapers with multi-objective genetic optimisation for vibration control of a single-link flexible manipulator”, Engineering Appoications of Artificial Intelligence, vol 21, no 2, 2008, 229-246.
[6] M. Tinkir; M. Kalyoncu; Y. Sahin, “Modelling and Controller Design for a Flexible Structure System against Disturbance Effects”, Journal of Low Frequency Noise Vibration and Active Control, vol 34, no 4, 2015, 525-548.
[7] B.Wajdi, B.Olfä, “Multivariable PID Control Via ILMI’s Performances Assessment”, International Journal on Smart Sensing and Intelligent Systems vol 8, no 4, 2015, 1896-1916.
[8] M.H.M. Shah, M.F. Rahmat, K.A. Danapalasingam and N.A. Wahab, “PLC based adaptive fuzzy PID speed control of DC belt conveyor system”, International Journal on Smart Sensing and Intelligent Systems, vol. 6, no 3, 2013, 1133-1152
[9] J.T. Agee, S. Kizir, Z. Bingul, “Intelligent proportional-integral (iPI) control of a single link flexible joint manipulator”, Journal of Vibration and Control, vol 21, no 11, 2015, 2273-2288.
[10] P.P. Zhu, C. Badong Chen, J.C. Principe, “A novel extended kernel recursive least squares algorithm”, Neural Networks, vol 32, 2012, 349-357.
[11] M. Omar, M. A. Zaidan, M. O. Tokhi, “Dynamic modelling and control of a twin-rotor system using adaptive neuro-fuzzy inference system techniques”, Proceedings of the Institution of Mechanical Engineers Part G-Journal of Aerospace Engineering, vol 226, no G7, 2012, 787-803.
[12] A. Sarkheyli, A.M. Zain, S. Sharif, “Robust optimization of ANFIS based on a new modified GA”, Neurocomputing, vol 166, 2015, 357-366.