A new approach for interval type-2 by using adaptive network based fuzzy inference system

Mustafa TINKIR

Department of Mechanical Engineering, Faculty of Engineering and Architecture, Selçuk University, Alaeddin Keykubat Campus, 42079 Konya, Turkey. E-mail: mtinkir@selcuk.edu.tr. Tel: +90 332 2232753. Fax: + 90 332 2385275.

Accepted 23 July, 2011

In this paper, adaptive network based fuzzy inference system (ANFIS) was used in control applications of different type nonlinear systems as interval type-2 fuzzy logic controller (IT-2FL). Two adaptive network based fuzzy inference systems were chosen to design type-2 fuzzy logic controllers for each control application. Membership functions in interval type-2 fuzzy logic controllers were set as an area called footprint of uncertainty (FOU), which is limited by two membership functions of adaptive network based fuzzy inference systems; they were upper membership function (UMF) and lower membership function (LMF). The double inverted pendulum, a single flexible link and a flexible link carrying pendulum systems were used to test the performances of designed interval type-2 fuzzy logic controllers. System behaviours were defined by Lagrange formulation and MATLAB/SimMechanics computer simulations. The performances of the proposed controllers were evaluated and discussed on the basis of the simulation results. An experiment set up of flexible link carrying pendulum system was built and used to verify the performance of IT-2FL controller.

Key words: Adaptive network based fuzzy inference system, interval type-2, inverted pendulum, a single flexible link, control, simulation.

INTRODUCTION

Fuzzy logic controller (FLC) is credited with being an adequate methodology for designing robust controllers that are able to deliver a satisfactory performance in applications where the inherent uncertainty makes it difficult to achieve good results using traditional methods (Mamdani, 1994). As a result, the FLC has become a popular approach to nonlinear systems such as robot control in recent years (Tinkir et al., 2010; Banga et al., 2011). Some of these investigations on the control of robot manipulators consider adaptive network based fuzzy logic control and hierarchical fuzzy logic control (Tinkir et al., 2010; Akbarzadeh et., 1994; Lin, 2002, 2003; Caswara et al., 2002; Kuo et al., 2002; Jassbi et al., 2011) due to their several advantages over other control techniques.

Fuzzy sets (of type-1) and fuzzy logic are the basis for fuzzy systems, where their objective has been to model how the brain manipulates inexact information. Type-2 fuzzy sets are used to control uncertainty and imprecision in a better way. These type-2 fuzzy sets were originally presented by Zadeh (1975) and are essentially “fuzzy fuzzy” sets, where the fuzzy degree of membership is a type-1 fuzzy set (Zadeh, 1988; Castillo et al., 2008). The new concepts were introduced (Liang et al., 2000; Mendel, 2001; Adak et al., 2011) allowing the characterization of a type-2 fuzzy set with a superior membership function and an inferior membership function; these two functions can be represented, each one by a type-1 fuzzy set membership function. The interval between these two functions represents the footprint of uncertainty (FOU), which is used to characterize a type-2 fuzzy set. While traditionally, type-1 FLCs have been employed widely in nonlinear systems’ control, it has become apparent in recent years that the type-1 FLC cannot fully handle high levels of uncertainties as its MFs (membership functions) are in fact completely crisp (Hagras, 2004; Mendel, 2001; Adak et al., 2011). The linguistic and numerical uncertainties associated with dynamic unstructured environments cause problems in determining the exact and precise MFs during the system FLC design. Moreover, the designed type-1 fuzzy sets can be sub-optimal under specific environmental and operational
introduction to consideration by this approach in most of the cited investigations, despite some of its advantages indicated in this study. Proposed type-2 fuzzy logic controller combines two different control techniques which are adaptive network based fuzzy logic inference system control and interval type-2 fuzzy logic control, and uses their control performances together. Adaptive network based fuzzy inference system (ANFIS) uses a hybrid learning algorithm to identify parameters of Sugeno-type fuzzy inference systems. A combination of the least-squares method and the backpropagation gradient descent method is used in training fuzzy inference system (FIS) membership function parameters to emulate a given training data set.

Initially, equations of motion of proposed systems were obtained by using Lagrange formulation for numerical simulations. Moreover MATLAB/SimMechanics toolbox and computer aided design program (SolidWorks) was used together for visual simulations. Two adaptive network based fuzzy logic inference systems were designed and used to control different type nonlinear systems. The double inverted pendulum, a single flexible link and flexible link carrying pendulum systems were chosen such as nonlinear systems and they were controlled by proposed IT-2FL controllers. In addition, an experiment set up was built for flexible link carrying pendulum system to verify the performance of proposed IT-2FL controller and the results of Lagrange formulation, SolidWorks modeling and, experimentally they were compared in same control figures.

DYNAMIC MODELING OF THE PROPOSED SYSTEMS

The aim of this paper is to model a new approach for interval type-2 fuzzy logic controller by using adaptive network based fuzzy inference system. Three interval type-2 fuzzy logic controllers were designed and used to control different type nonlinear systems. Double inverted pendulum, a single flexible link and flexible link carrying pendulum systems were chosen such as nonlinear systems and they were controlled by proposed IT-2FL controllers to show efficiency of IT-2FL control and verify validity of this new approach.

Equations of motion of the double inverted pendulum system

The most important characteristic of double inverted pendulum system shown in Figure 1 is that the number of actuator of system is less than the system’s number of degree of freedom. Double inverted pendulum system with this characteristic differs from two degrees of freedom of rigid link of robotic systems. The system parameters were given in Table 1. The goals of applied controllers to robotic systems and double inverted pendulum system are different. While the control in robotic systems, that is, taking robot arm to desired position, the purpose of the control of the double
The control torque was expressed by input vector as:

\[
\tau = \begin{bmatrix} \tau_1 \\ 0 \end{bmatrix}
\]  

(3)

The goal of the control that was applied to the double inverted pendulum system was to supply output values of the system equal to reference value. The control action was that it produces appropriate input torque to feed the system for the system to realized desired motion. By another expression, it was that desired output value was obtained from the system, as a result of the applied convenient input value to system. The applied input to the double inverted pendulum system was motor torque and output of the system was angles of pendulums with vertical direction. The purpose of the designed controller for the system was to get the pendulums to unstable equilibrium point in minimum time and to supply motor torque that provides position of the pendulums in tolerance range.

Earlier studies about pendulum systems were realized to find dynamic model by using Euler and Lagrange equations. In this study, dynamic model of the system was obtained by using both Lagrange formulation and MATLAB/SimMechanics toolbox. System parameters were used for modeling of system. By means of this approach dynamic modeling becomes easy and clear. SimMechanics modeling and control block diagram of double inverted pendulum system were given in Figure 2.

### Equations of motion of a single flexible link system

The schematic diagram of the flexible robot manipulator was given in Figure 3. This considered robot arm consisted of a flexible beam with a distributed mass. The mass and flexible properties were assumed to be distributed uniformly along the flexible arm. The flexible arm was assumed as an Euler-Bernoulli beam. \( \theta \) represented the angular position of the equivalent rigid link with respect to the fixed frame \( XY \). \( D \) represented the position of the end point on the flexible arm with respect to the equivalent rigid link. Assuming small deflection of the link, an approximate linear time invariant dynamic model was derived using Lagrange formulation and the dynamic equation was represented in matrix form as:

\[
M \ddot{q} + C \dot{q} + K q = F
\]

(4)

where the vector \( q \) is generalized coordinates, \( q=[\theta \quad \alpha]^{T} \), \( M \) is the mass matrix, \( C \) is the damping matrix, \( K \) is the stiffness matrix and \( F=[T \quad 0]^{T} \) and \( T \) is the input torque applied at the joint. The variable \( \alpha \) (\( \alpha=-D/L \)) represented the slope at the free end of the flexible link.

The dynamic model was represented in state-space form as:

\[
x = A \dot{x} + B u
\]

\[
y = C x
\]

(5)

Table 1. The parameters of double inverted pendulum system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of first pendulum, ( m_1 )</td>
<td>0.2</td>
<td>kg</td>
</tr>
<tr>
<td>Mass of second pendulum, ( m_2 )</td>
<td>0.5</td>
<td>kg</td>
</tr>
<tr>
<td>Length of first pendulum, ( l_1 )</td>
<td>0.1</td>
<td>m</td>
</tr>
<tr>
<td>Length of second pendulum, ( l_2 )</td>
<td>0.3</td>
<td>m</td>
</tr>
</tbody>
</table>
The matrices $V$ modeled as a beam rotating around z-axis. Lagrange formulation both kinetic and potential energy terms of pendulum by (a) top view and (b) front view of system. Where the vector $x = [\theta \alpha \dot{\theta} \dot{\alpha}]^T$, the matrices $A$, $B$, and $C$ were given by:

$$A = \begin{bmatrix} 0_{2 \times 2} & I_{2 \times 2} \\ -M^T K & -M^T C \end{bmatrix}, \quad B = \begin{bmatrix} 0_{2 \times 1} \\ -M^T \end{bmatrix}, \quad C = I_{2 \times 4}$$

Equations of motion of flexible link carrying pendulum system

The dynamic model of the flexible link carrying a pendulum system was obtained by Lagrange formulation, 3D solid modeling technique and MATLAB/SimMechanics toolbox (Tınkır et al., 2010). Figure 4 depicts the simplified system with flexible link and pendulum by (a) top view and (b) front view of system. According to Lagrange formulation both kinetic and potential energy terms of flexible link and pendulum were obtained. The flexible link was modeled as a beam rotating around z-axis. Lagrange formulation was described $L = T - V$ and where $T$ is total kinetic energy and $V$ is total potential energy of system:

$$T = \frac{1}{2} J_{hub} \dot{\theta}^2 + \frac{1}{2} J_{link} (\dot{\theta} + \dot{\eta})^2 + \frac{1}{2} M_{pendulum} \dot{V}_s^2$$

$$V = \frac{1}{2} K \eta^2 + M_s g l (1 - \cos \varphi)$$

According to aforementioned equations, five equations of motion were written to define dynamic behavior of system as follows:

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \theta} \right) - \frac{\partial L}{\partial \dot{\theta}} = T_L - B \dot{\theta}$$

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}} \right) - \frac{\partial L}{\partial \ddot{\theta}} = 0$$

where $[\theta, \eta, \varphi, \dot{\varphi}, \alpha_l]$ was defined as generalized coordinate vector, $T_l$ is actuated torque and $B$ is damping coefficient.

By using Lagrange formulation, equations of motion were obtained and the proposed modeling technique called as 3D solid modeling method was realized (Tınkır et al., 2010). For this purpose, firstly flexible link and pendulum system was drawn in respect of the actual experiment set up in SolidWorks CAD program. The psychical properties of flexible link and pendulum were considered such as material, dimensions and thickness of link. Ceramic billiards ball was used for modeling tip mass of pendulum. In servo, plant gears and a DC servo motor were assumed as a revolute joint. This approach was verified at the end of the paper when Lagrange formulation and 3D solid modeling method results were compared. Figure 5a shows that computer aided model design of flexible link carrying pendulum system. Computer aided CAD model was converted into the MATLAB/SimMechanics program via ‘Solid to MATLAB’ converter program. SimMechanics model was given in Figure 5b. This model was simulated and controlled to figure out the dynamic behaviour of flexible link carrying pendulum system without using complex differential equations. In this manner, differential equations which are mostly used in dynamic modeling of systems are not needed any more. Moreover, we can implicate real system properties to our model as material (stainless steel flexible link) by such way.

THE DESIGN OF INTERVAL TYPE-2 FUZZY LOGIC CONTROLLERS

In this study, six adaptive network based fuzzy inference system (ANFIS) controllers were designed and applied to nonlinear systems to control positions, vibrations and oscillations. These systems were defined before as double inverted pendulum, a single flexible link and flexible link carrying pendulum systems. Two of the six ANFIS controllers were used for control of each system with different type membership functions and different number of rule bases. Moreover these two ANFIS controllers were combined to create an interval type-2 fuzzy logic controller. Eventually an interval type-2 fuzzy logic controller was obtained for each proposed systems by using six different type adaptive network based fuzzy inference systems.

The adaptive network based fuzzy inference system (ANFIS) uses a hybrid learning algorithm to identify the parameters of the Sugeno type fuzzy inference systems. It applies a combination of the least-squares method and the back propagation gradient descent method for training the fuzzy inference system (FIS) membership function parameters to emulate a given training data set.

In this paper, the forward hybrid learning algorithm is used for the neural network part of the ANFIS controllers shown in Figure 6a. The hybrid learning algorithm was described in the literatures.
Figure 4. (a) The flexible link carrying pendulum system. (b) The front view of system.

Figure 5. (a) Computer aided model. (b) SimMechanics model.

Figure 6. (a) TSK fuzzy inference system with two inputs and two rules. (b) Architecture of ANFIS of first order TSK model with two inputs.
elements of \( S_1 \), we can plug \( P \) training data into Equation 17 and obtain a matrix equation:

\[
f = \begin{bmatrix} w_1 x & -w_1 y & -w_2 x & -w_2 y & -w_3 \end{bmatrix} = X W \quad (18)
\]

where \( X \) is input matrix and \( W \) is a weight vector (firing strength of node) and can easily be modified.

Lemma 1

The inverse \( X' \) of a matrix \( X \) exists only if \( X \) is square and has full rank. In this case, \( f = X W \) has the solution \( W = X^{-1} f \).

Lemma 2

The pseudo-inverse \( X' \) (beware, it is often denoted otherwise) is a generalization of the inverse, and exists for any \( m \times n \) matrix. We assume \( m \geq n \), if \( X \) has full rank (\( n \) defined by us):

\[
X' = \left( X^T X \right)^{-1} X^T \quad \text{and the solution of} \quad f = X W \quad \text{is} \quad W = X' f \quad \text{otherwise a pseudo-inverse (X')} \quad \text{of} \quad X \quad \text{is used to solve for} \quad W:
\]

\[
W = \left( X^T X \right)^{-1} X^T f \quad (19)
\]

where \( X^T \) is the transpose of \( X \), and \( \left( X^T X \right)^{-1} \) is the pseudo-inverse of \( X \) if \( X^T X \) is non-singular. While Equation 19 is concise in notation, it is expensive in computation when dealing with the matrix inverse and, moreover, it becomes ill-defined if \( X^T X \) is singular. As a result, we employ sequential formulas to compute the LSE of \( X \). This sequential method of LSE is more efficient (especially when \( M \) is small) and can easily be modified to an on-line version for system with changing characteristics. Specifically, let the \( i \) th row vector of matrix \( X \) defined in Equation 18 be \( a_i^T \) and the \( i \) th element of \( f \) be \( b_i^T \), then \( W \) can be
calculated iteratively using the sequential formulas widely adopted in the literature (Goodwin et al., 1984; Ljung, 1987; Strobach, 1990; Lin, 2005):

\[
W_{i+1} = W_i + S_{i+1}a_{i+1} \left( b_i^* - a_i^* W_i \right)
\]

\[
S_{i+1} = S_i - \frac{S_i a_i^* a_i^* S_i}{1 + a_i^* S_i a_i^*}, i = 0, 1, \ldots, P - 1
\]

where \( S_i \) is often called the co-variance matrix and the least squares estimate \( W^* \) is equal to \( W_i \). The initial conditions to bootstrap Equation 20 are \( W_0 = 0 \) and \( S_0 = \mathcal{M} \), where \( \mathcal{M} \) is a positive large number and \( \mathcal{I} \) is the identity matrix of dimension \( M \times M \). When dealing with multi-output adaptive networks (output in Equation 15 is a column vector), Equation 20 still applies except that \( b_i^* \) is the \( i \)-th rows of matrix \( f \).

When the premise parameters are not fixed, the search space becomes larger and the convergence of the training becomes slower. A hybrid algorithm combining the least-squares method and the gradient descent method is adopted to solve this problem. The hybrid algorithm is composed of a forward pass and a backward pass. The least-squares method (forward pass) is used to optimize the consequent parameters with the premise parameters fixed. Once the optimal consequent parameters are found, the backward pass starts immediately. The gradient descent method (backward pass) is used to adjust optimally the premise parameters corresponding to the fuzzy sets in the input domain. The output of the ANFIS is calculated by employing the consequent parameters found in the forward pass. The output error is used to adapt the premise parameters by means of a standard backward pass algorithm. It has been proven that the hybrid algorithm is highly efficient in training the ANFIS (Jang, 1993). In this study, checking data was chosen from some part of training data and the convergence of one of the ANFIS controllers for a single flexible link was given in Figure 7.

Fuzzy control is by far the most successful applications of the fuzzy set theory and fuzzy inference systems. Due to the adaptive capability of ANFIS, its applications to adaptive control and learning control are immediate. For this purpose, the adaptive network-based fuzzy inference system has been used to optimize the fuzzy IF-THEN rules and the membership functions to derive a more efficient fuzzy control. The proposed ANFIS model combined the neural network adaptive capabilities and the fuzzy logic qualitative approach (Zadeh, 1989). Intelligent systems based on fuzzy logic are fundamental tools for nonlinear complex system control. Type-2 fuzzy sets are used to control uncertainty and imprecision in a better way. These type-2 fuzzy sets were originally presented by Zadeh (1975) and are essentially “fuzzy fuzzy” sets where the fuzzy degree of membership is a type-1 fuzzy set (Zadeh, 1989). The new concepts were introduced by Liang and Mendel allowing the characterization of a type-2 fuzzy set with a superior membership function and an inferior membership function; these two functions can be represented each one by a type-1 fuzzy set membership function.

The interval between these two functions represents the footprint of uncertainty (FOU), which is used to characterize a type-2 fuzzy set shown in Figure 8. Structure of interval type-2 fuzzy logic inference system was given in Figure 9. After all these instructions about ANFIS and interval type-2 fuzzy inference systems, ANFIS controllers were used in control applications, then IT-2FL controllers were built according to performances of ANFIS controllers over the double inverted pendulum, a single flexible link and flexible link carrying pendulum systems. Realization phases of this study were given in Figure 10. Explanation of first and second type controllers was shown in Table 2.

**Membership functions of IT-2FL controllers**

The membership functions of IT-2FL controller for double inverted pendulum system were given in Figure 11. Ten rules were used and two rules were described as an example:

1. If position error of first pendulum is NEGATIVE BIG then control action is \( CV_1 \).
2. If position error is first pendulum POSITIVE BIG then control action is \( CV_2 \).

The membership functions of IT-2FL controller of a single flexible link system were given for position error input in Figure 12. There are ten fuzzy membership functions that correspond to zero (Z), positive (P), positive medium (PM), positive big (PB) and positive big big (PBB) values of position error.

Same linguistic variables were used for gbell and triangular type membership functions. Rule base of IT-2FL controller for a single flexible link system was described as:

1. If position error is \( Z \) or \( P \) then control action is \( CV_1 \).
2. If position error is \( Z \) or \( P \) then control action is \( CV_2 \).
3. If position error is \( Z \) or \( P \) then control action is \( CV_3 \).
4. If position error is \( Z \) or \( P \) then control action is \( CV_4 \).
5. If position error is \( Z \) or \( P \) then control action is \( CV_5 \).

Here \( CV_i \) (\( i = 1, 2, \ldots \)) is constant value of IT-2FL controller's output, zero (Z), positive (P), positive medium (PM), positive big (PB) and positive big big (PBB) linguistic variables are divided to two parts such as \( P = [P, P] \).

IT-2FL controller’s membership functions for flexible link carrying pendulum system were given in Figure 13. There are seven fuzzy membership functions that correspond to zero (Z), positive (P), positive medium (PM), positive big (PB) and positive big big (PBB) values of rotation error. Same linguistic variables are used for gauss and triangular type membership functions.

Rule base of IT-2FL controller for flexible link carrying pendulum system was described as:

1. If rotation error is \( Z \) then control action is \( CV_1 \).
2. If rotation error is \( Z \) then control action is \( CV_2 \).
3. If rotation error is \( Z \) then control action is \( CV_3 \).
4. If rotation error is \( Z \) then control action is \( CV_4 \).

**Defuzzification process**

Once the fuzzy controller is activated, the rule evaluation is performed and all the rules which are true are fired. Utilizing the true output membership functions, the defuzzification is then applied to determine a crisp control action. The defuzzification is to transform the control signal into an exact control output. For the Sugeno-style inference, we have to choose between wtaver (weighted average) or wtsum (weighted sum) defuzzification method. In the defuzzification process of the adaptive network based fuzzy logic controller, the method of weighted average (wtaver) is used:

\[
u = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i}
\]
Figure 7. (a) Input data. (b) Convergence of ANFIS after training. (c) Checking of ANFIS.

Figure 8. Definition of membership functions of interval type-2 fuzzy logic inference system.
Table 2. Explanation of first and second type controllers.

<table>
<thead>
<tr>
<th>The proposed systems</th>
<th>First controllers</th>
<th>Second controllers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double inverted pendulum</td>
<td>Two ANFIS type controllers</td>
<td>Interval type-2 fuzzy logic controller</td>
</tr>
<tr>
<td>A single flexible link</td>
<td>Two ANFIS type controllers</td>
<td>Interval type-2 fuzzy logic controller</td>
</tr>
<tr>
<td>Flexible link carrying pendulum</td>
<td>Two ANFIS type controllers</td>
<td>Interval type-2 fuzzy logic controller</td>
</tr>
</tbody>
</table>

Figure 9. Structure of interval type-2 fuzzy logic inference system.

Figure 10. Realization phases of the study.

Figure 11. Membership functions of IT-2FL controller for double inverted pendulum system.
RESULTS AND DISCUSSION

The effectiveness of the proposed controller has been tested by simulations. The objective in first simulation was to tune controllers for swing-up control of double inverted pendulum system. The proposed controller allowed us to command a desired angle position and eliminate oscillations while maintaining a fast response. Objective of control was chosen to get pendulums to vertical position. Position angles were chosen 90° and 0° for first pendulum and second pendulum, respectively. Simulations were done in respect to this task. In this way step reference input was given for desired input signal of control system. Feedback signal of first pendulum angle was used to tune controllers. PID (Proportional-Derivative-Integral) control technique was tried and used to compare with the performance of IT-2FL controller. The performance criterions of designed controller are chosen as:

1. Maximum oscillation angels of the pendulums $\leq 30^\circ$
2. Pendulum’s settling time is 2 s.

Performances of PID controller were given in Figures 14 and 15. From these results, it can be said that the PID controller is effective over the system. But according to performance criterions PID controller is not appropriate. The IT-2FL controller increased the PID control performance on the double inverted pendulum system. Figures 16 and 17 show performances of IT-2FL controller.
Figure 14. PID control of pendulum 1 angle.

Figure 15. PID control of pendulum 2 angle.

Figure 16. IT-2FL control of pendulum 1 angle.
From these results we can say that IT-2FL controller provides performance criterions and it is effective for swing-up control of double inverted pendulum system. Visual simulation of controlled system was given in Figure 18.

The objective of the second simulation was to tune IT-2FL controller for position and tip deflection control of a single flexible link manipulator. The controller allowed us to command a desired tip angle position and eliminate the link's vibrations while maintaining a fast response. Objective of flexible manipulator was chosen that moving to 30° degree of rotation. Simulations were done in respect to this task. In this way, step reference input was given for desired input signal of control system. Position and tip deflection control responses of IT-2FL controller were given in Figures 19 and 20.

According to Figures 19 and 20, the performance of IT-2FL controller was increased gradually by using ANFIS controllers. Neural network base of ANFIS toolbox developed to learning capacity of IT-2FL controller. As shown in Figure 19, the proposed IT-2FL controller brought to flexible link to desired position without maximum overshoot and steady state error. Moreover IT-2FL controller has good tip deflection response in Figure 20. The performance results of the proposed controller were given in Tables 3 and 4 for position and tip deflection control. From these results, it can be said the IT-2FL controller is a more effective controller for control of a single flexible link manipulator system. The reason is that ANNIT2FL controller has two different type membership functions and it is consisted of two ANFIS type controllers. The objective of the scaled tower crane system was chosen that moving to thirty degree of rotation. Simulations and experiments were realized in respect to this task. In this way step reference input was given for desired input signal of the control system. Position and tip deflection performances of the IT-2FL controller were given in Figures 21 and 22. According to Figures 21 and 22, it can be said that simulation results obtained by using SolidWorks modeling technique and Lagrange formulation were close to experimental results. Moreover IT-2FL controller has good control performances over position and tip deflection control. The proposed IT-2FL control decreased position steady state error of flexible link effectively.

In addition IT-2FL control terminated pendulum oscillation effects over position response of the system. The proposed IT-2FL control was applied to scaled tower crane system successfully both simulation and experimental works, because the IT-2FL controller's base depends on the two ANFIS type controllers training data sets. Pendulum swing angles defined as \( [\varphi, \phi, \alpha_L] \) of IT-2FL controlled system were simulated according to SolidWorks modeling technique and Lagrange formulation in Figures 23 and 24, respectively. Both simulation and experimental works “\( \phi \)” swing angle of pendulum was defined as critical swing angle which affected position and vibration control more than other swing angles called as “\( \varphi, \alpha_L \)”. Because the plane of swing angle “\( \phi \)” was the same with rotary plane “\( x \)” of the flexible link. The simulation and experimental results already obtained about swing angles showed that “\( \varphi, \alpha_L \)” angles were observed smaller than swing angle “\( \phi \)”. According to Figures 23 and 24, swing angles \( [\varphi, \phi, \alpha_L] \) were reduced and ended after 4.5 s in simulations. The results obtained simulations with SolidWorks modeling technique were close to simulation results by Lagrange formulation. In addition, swing angle results in Figure 23 were found smaller than obtained results in Figure 24. So these results showed that SolidWorks modeling technique can be used to obtain dynamic behaviors of the proposed systems without using mathematical
Figure 18. Visual simulation of the double inverted pendulum system (under IT-2FL control).

equations. The critic swing angle “ϕ” results of IT-2FL controlled system were compared experimentally and given in Figure 25. The critic swing angle “ϕ” was measured during experimental works by using image
Figure 19. IT-2FL position control response of a single flexible link manipulator.

Table 3. Performance comparison of proposed controllers for position control.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Rise time</th>
<th>Settling time</th>
<th>Maximum overshoot</th>
<th>Steady state error</th>
</tr>
</thead>
<tbody>
<tr>
<td>IT-2FL</td>
<td>0.35 s</td>
<td>0.6 s</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4. Performance comparison of proposed controllers for tip deflection control.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Maximum deflection</th>
<th>Damping time</th>
<th>Permanent vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>IT-2FL</td>
<td>2.5°</td>
<td>0.9 s</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 20. IT-2FL tip deflection control response of a single flexible link manipulator.

Figure 21. IT-2FL position control response of flexible link carrying pendulum system.
Figure 22. IT-2FL tip deflection control response of flexible link carrying pendulum system.

Figure 23. Swing angles responses of IT-2FL controller by SolidWorks modeling.

Figure 24. Swing angles responses of IT-2FL controller by Lagrange formulation.
Conclusions

In this paper, adaptive network based fuzzy inference system (ANFIS) was used in control applications of different type nonlinear systems as interval type-2 fuzzy logic controller (IT-2FL). Two adaptive network based fuzzy inference systems were chosen to design type-2 fuzzy logic controllers for each control applications. The double inverted pendulum, a single flexible link and a flexible link carrying pendulum systems were used to test the performances of designed interval type-2 fuzzy logic controllers. System behaviours were defined by Lagrange formulation and MATLAB/SimMechanics computer simulations. The performances of the proposed controllers were evaluated and discussed on the basis of the simulation and experimental results. The proposed IT-2FL controller has good performance over different type nonlinear systems according to its structure. ANFIS type controllers were used to obtain IT-2FL controller and different type membership functions were used together to determine ideal fuzzy logic controllers in terms of interval type-2 fuzzy logic. Owing to this new approach different ANFIS type controllers can be used with their different types of membership functions into one IT-2FL controller. In this manner IT-2FL controller has two ANFIS type controllers’ performances and their adaptive capacities. Another result of this study is that SolidWorks modeling technique can be used instead of Lagrange formulation to obtain dynamic system behaviour. It was verified with the results of Lagrange formulation and experimental results. In the future, more effective approaches to the realtime performance of the interval type-2 fuzzy logic control will be investigated. Moreover the proposed type-2 control will be used in the control strategy of different nonlinear systems such as position and vibration control of the earthquake platform (with single and double storey), feedback position control of the flexible robot over earthquake platform and exo-skeleton motion control.

ACKNOWLEDGMENT

This work is supported by the coordinatorship of Selçuk University’s Scientific Research Projects (Project no.: 06401020).
REFERENCES


