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Development of Neural Network Controller for A Two-Link Flexible Manipulator

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***Abstract*— This paper discusses a neural network (NN) control of a two-link flexible robot manipulator. The PID controller was formerly used to solve nonlinearities problem. One more efficient solution for nonlinearities problem is NN. An evaluation was conducted to assess the performances of the controller in the areas of the input tracking controller capability of the system compared to PID control. Furthermore, it is analyzed the robustness of the NN based on PID control schemes. The results showed that NN based on PID controller demonstrated better performance.**

***Keywords*— control, neural network, the two-link flexible robot manipulator**

I. INTRODUCTION

An accurate model of an actual system behavior can be accomplished by modeling a two-link flexible manipulator. It is crucial to recognize the flexible nature of the system and identify the dynamic characteristics of the system to construct the appropriate mathematical framework. Previous works on modeling a single-link flexible manipulator using an Assumed Mode Method (AMM) suggested that first two modes can be used to determine dynamics of flexible manipulators. The results showed that the experiment results were relevant to the theory used [1]. The complex modeling process rises significantly compared to a single-link flexible manipulator. Dogan and Istefanopulos [2] made finite element models to explain the deflection of a planar two-link flexible robot manipulator. De Luca and Siciliano [3] proposed a dynamic model of multilink flexible robot arms limited to the case of planar manipulators with no torsional effects derived with AMM. A systematic approach to dynamic equations of n-link manipulator with matrices of two transformations with homogeneity to explain motions with rigid and flexible characters was referred to Subudhi and Morris [4].

Currently, control strategies using two-link flexible manipulators are most intriguing issues. Control inputs and external disturbances cause flexural vibrations inside the manipulator structures which exacerbate the difficulties of flexible manipulator control. A number of proposed control methods for two-link flexible manipulator control has been introduced. Shengping et. al. [5] created A PD controller to provide stabilization of the robot system after capturing objects. Two cases were dynamically simulated: the robot system was uncontrolled, but then controlled after the impact. Payo et al [6] implemented a PID controller for forced and constrained motions of flexible manipulators. It has also been developed a PD control for controlling vibration from a single-link flexible manipulator equipped with an array on fiber optic curvature sensors and also PZT actuators [7]. A study conducted by Tian and Collin [8] used a learning controller and a feed forward controller for controlling the system of a two-link flexible manipulator. Over the feedback loop, the manipulator system was equipped with a fuzzy logic controller to produce control signals. Over the learning controller, recurrent neural network which is dynamic hold a state feedback. A back-propagation neural network and models the inverse dynamics of the manipulator system give less computational advantages. Gutierrez [9] demonstrated a better performance of tracking from the NN controller compared with PD or PID standard controllers. Adaptive neuron-fuzzy control was confirmed by Tian and Collin [10] to provide satisfactory control of a single link flexible manipulator. Subudhi and Moris [11] created a multi-link flexible manipulator using a hybrid fuzzy neural control scheme. A strategy to track the end-point from a manipulator with a single-link flexible was applied.

However, existing studies concerning neural networks were conducted through simulation exercises with limited experimental validation. Furthermore, works using NN based PID controller for a two-link flexible manipulator with payloads are limited. Reports on NN controller used by a two-link flexible manipulator with payloads are also insufficient. This is a demand faced by a MIMO system and the system behavior. It is influenced by a lot of factors. The dynamic modeling and NN control used by a two-link flexible robot manipulator integrating payload was the main concern in this paper. A payload is attached at the end-point of the second-link, whereas hub inertias are designed at the actuator joints. The dynamic model was simulated with Matlab and Simulink. An evaluation was performed to assess system responses that include hub angular position and deflection. In addition, the works analyze impacts on the system's dynamic characteristics resulted from payload variations. The basis for suitable control strategies design and development for the two-link flexible manipulator systems was also proposed in this study.

II. NN CONTROL OF A TWO-LINK FLEXIBLE MANIPULATOR

A. Modeling of A two-Link Flexible Manipulator

The total energies related to the manipulator system have to be computed through kinematics formulations in the process of developing the dynamic equations for motion of a two-link flexible manipulator. It can be defined the total of kinetic energy with:

$$T = T_R + T_L + T_{PL} \tag{1}$$

Where TR, TL, and TPL are the kinetic energies related with rotors, links and the hubs respectively.

Moreover, the derivative time from the global transformation matrix $\dot{T}_i$ can be obtained recursively with [3], [4]:

$$\dot{T}_i = \dot{\hat{T}}_{i-1} A_i + \dot{\hat{T}}_{i-1} \dot{A}_i \, , \; \dot{\hat{T}}_i = T_i E_i + T_i \dot{E}_i \tag{2}$$

The total of potential energy from the system caused by deformation of the link i by ignoring gravity effects can be calculated using the following formula:

$$U = \sum_i^n \frac{1}{2} \int_0^{l_i} (EI)_i \left(\frac{d^2 \upsilon_i (x_i)}{d{x_i}^2} \right)^2 dx_i \tag{3}$$

Where EI is defined as the flexural rigidity system.

Euler-Beam theory can be used to write the link at an arbitrary spatial point xi dynamics on the link at a moment of time t as

$$(EI)_i \frac{\partial^4 \upsilon_i (x_i, t)}{\partial {x_i}^4} + \rho_i \frac{\partial^2 \upsilon_i (x_i, t)}{\partial t^2} = 0 \tag{4}$$

On contrary, bending deflections $\upsilon_i(x_i, t)$ can be presented as a mode-shapes superposition and displacements of time-dependent modals as

$$\upsilon_i (x_i, t) = \sum_{j=1}^{n_m} \phi_{ij} (x_i) q_{ij} (t) \tag{5}$$

Where $q_{ij}(t)$ and $\phi_{ij}(x_i)$ are the jth modal displacement and jth mode shape function for the ith link. The solution of equation (19) is in the form of

$$\begin{aligned} \phi_{ij}(x_i) = m_i[\cos(\beta_{ij} x_i) - \cosh(\beta_{ij} x_i + \\ \gamma_{ij} (\sin(\beta_{ij} x_i) - \sinh(\beta_{ij} x_i))] \end{aligned} \tag{6}$$

Where m_i is the mass of link i and γ_{ij} is given as

$$\gamma_{ij} = \frac{\sin \beta_{ij} - \sinh \beta_{ij} + \frac{M_{L_i} \beta_{ij}}{\rho_i} (\cos \beta_{ij} - \cosh \beta_{ij})}{\cos \beta_{ij} + \cosh \beta_{ij} - \frac{M_{L_i} \beta_{ij}}{\rho_i} (\sin \beta_{ij} - \sinh \beta_{ij})} \tag{7}$$

In this study, a dynamic model of the system integrating payloads is investigated. In this case, the effectiveness masses at the end of the individual links (ML1 for link-1 and ML2 for link-2) are set as

$$\begin{aligned} M_{L1} &= m_2 + m_{h2} + M_p \\ M_{L2} &= M_p \end{aligned} \tag{8}$$

And the effective inertia of the individual links (JL1 for link-1 and JL2 for link-2) are

$$\begin{aligned} J_{L1} &= J_{o2} + J_{h2} + J_p + M_p l_2^2 \\ J_{L2} &= J_p \end{aligned} \tag{9}$$

Where m_2 is the mass of link 2 and Jo2 is the joint inertia of link-2 about the joint-2 axis.

The coordinate vector consists of link positions, (θ1, θ2) and modal displacements (q11, q12, q21, q22). The force vector is F = {τ1, τ2, 0, 0, 0, 0} T, where τ1 and τ2 are the torques implemented at the hubs of link-1 and link-2, respectively. The Euler–Lagrange"s equations with the Langrangian, $L = T - U$ can be used to derive the dynamic equations for a two-link flexible manipulator motions. With i = 1 and 2 and j = 1 and 2, it is defined as:

$$\frac{\partial}{\partial t} \left(\frac{\partial L}{\partial \dot{\theta}_i} \right) - \frac{\partial L}{\partial \theta_i} = \tau_i \tag{10}$$

And,

$$\frac{\partial}{\partial t} \left(\frac{\partial L}{\partial \dot{q}_{ij}} \right) - \frac{\partial L}{\partial q_{ij}} = 0 \tag{11}$$

The expected dynamic equations for a two-link flexible manipulator motions are defined by considering the damping in:

$$M(\theta,q)\begin{Bmatrix}\ddot{\theta}\\ \ddot{q}\end{Bmatrix}+\begin{Bmatrix}f_1(\theta,\dot{\theta})\\ f_2(\theta,\dot{\theta})\end{Bmatrix}+ \begin{Bmatrix}g_1(\theta,\dot{\theta},q,\dot{q})\\ g_2(\theta,\dot{\theta},q,\dot{q})\end{Bmatrix}+\begin{Bmatrix}0\\ D\dot{q}\end{Bmatrix}+ \begin{Bmatrix}0\\ Kq\end{Bmatrix}=\begin{Bmatrix}\tau\\ 0\end{Bmatrix} \quad (12)$$

B. Neural Network Controller Design

The input vector is sent to every m-th hidden node in which it is placed with the function of nodes radial basis:

$$y_m = f_m(x) = \exp[-\|x-c_m\|^2/(2\sigma^2)] \quad (13)$$

Where $\|x-c_m\|^2$ is the square of the distance between the input feature vector x and the center vector c_m for that radial basis function.

The values (y_m) are the outputs from the radial basis functions. These radial basis functions on a 2-dimensional feature space have the form shown in the simple graph below. The values equidistant from the center in all directions have the same values, so this is why these are called radial basis functions.

The outputs from the hidden layer nodes are weighted by the weights on the lines and the weighted sum is computed at each j-th output node as

$$z_j = (1/M)\sum_{(m=1,M)} u_{mj} y_m \quad (14)$$

The function of mean square error which should be minimized by parameters {umj} adjustment is found to be identical with the one for back propagation NN. However it is simpler to be minimized. Only one set of parameters exists instead of two as was the back propagation NNs case. After suppressing the index q has:

$$E = (1/J)\sum_{(j=1,J)} (t_j - z_j)^2 \quad (15)$$

Thus

$$\partial E/\partial u_{mj} = (\partial E/\partial z_j)(\partial z_j/\partial u_{mj}) = [(-2/J)\sum_{(j=1,J)} (t_j - z_j)](y_m/M) \quad (16)$$

After putting it into the steepest descent method

$$u_{mj}^{(k+1)} = u_{mj}^{(k)} + [2\eta/(JM)]\sum_{(j=1,J)} (t_j - z_j)]y_m \quad (17)$$

Where η represents learning rate, also known as step size. After overall Q feature vector inputs and their respective target output vectors training, Equation (34) is written as:

$$u_{mj}^{(k+1)} = u_{mj}^{(k)} + [2\eta/(JM)]\sum_{(q=1,Q)}\sum_{(j=1,J)} (t_j^{(q)} - z_j^{(q)})]y_m^{(q)} \quad (18)$$

There is still some missing information before an algorithm can be applied for training a NN on a given data set {{x(q) : q = 1,...,Q}, {t(q) : q = 1,...,Q}} (here the feature vectors for training (the exemplar vectors) and paired with the target vectors by the index q). The center vectors {c(m) : m = 1,...,M} still cannot be identified. The center needs to determine the center for radial basis functions. It also doesn't know M and doesn't know the spread parameter σ.

III. Method

This study determines techniques to obtain two-link flexible robot manipulator control. First one is based on the Proportional-Integral-Derivative (PID) controller with its control by using NN controller based on PID controller. The stability, maximum overshoot, settling time, and several system performance indicators depend on values of Kp, Ki, and Kd. The control of a two link-flexible manipulator was achieved with A PID controller, Figure 1 presents the block diagram of a PID controller.

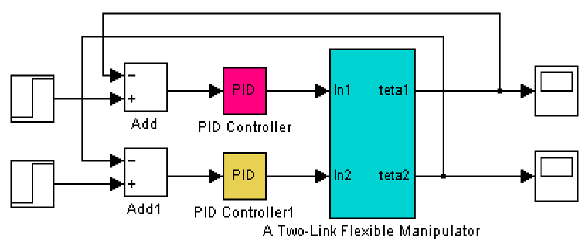

Fig. 1. The schematic of PID Controller

The control of two-link flexible manipulator systems was performed using Neural Network controller based PID controller. Figure 2 shows PID controllers based on Neural Network controllers.

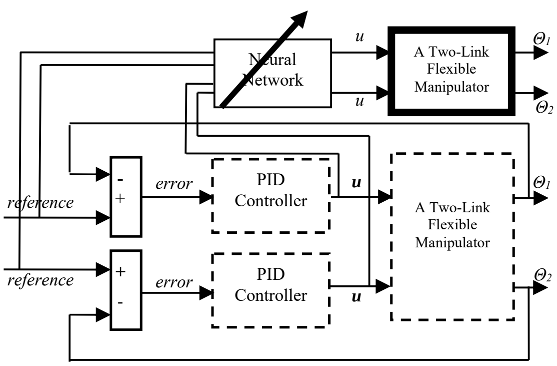

Fig.2. The structure of the neural network controller.

IV. Results and Discussion

The results of simulating NN based on PID control of the two-link flexible manipulator are drawn as follows. The manipulator utilized a step signal with a ±0.4 rad amplitude as an input position in radian applied at the hub of link-1. Link-2 used the same signal form with a ±0.8 rad amplitude. An evaluation was performed to analyze the three obtained system responses consisting of hub angular positions and deflections and also end-point acceleration for the links. The variations of payloads led to significant changes of time response specifications of angular positions. Comparing with PID, NN based PID controller stimulated the system to perform lower settling times. It also produced smaller overshoots for both links controller. It was also noted that the variations of payload affected the transient responses of the system. The summaries of the response from settling time and overshoot of the angular position with payload 0.3 kg utilizing NN based PID control and PID control are shown in Table 1.

The two-link flexible manipulator with various payloads was examined to determine the effects from payloads on the system's dynamic characteristics. If it was compared with PID controller, responses of the flexible manipulator system with 0.3 kg payloads for link-1 and link-2 using NN based PID controller could be shown in Fig 3 and Fig 4.

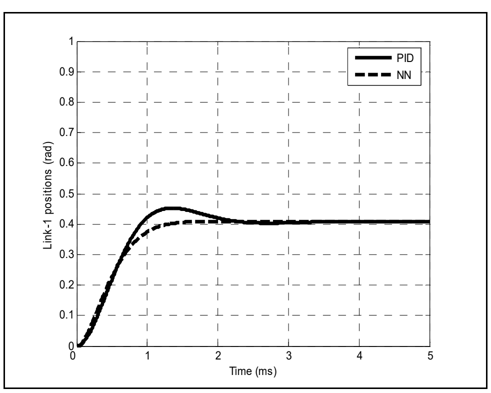

Fig.3. Angular position of Link-1

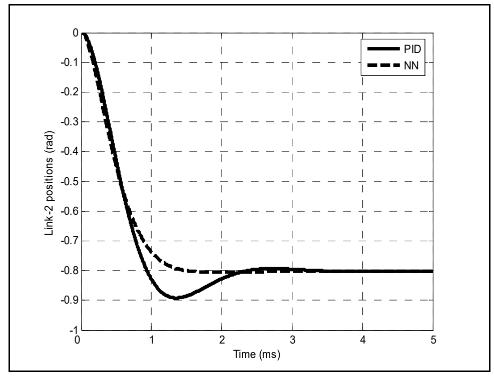

Fig. 4. Angular position of Link-2

The deflection responses of the two-link flexible manipulator for link-1 and link-2 with 0.3 kg payloads using NN based PID control and PID control are presented in Fig 5 and 6. It was concluded that the more payloads increased, the more the magnitudes of vibration of the deflection for both links would develop. On the other hand, if it was compared with PID control, NN based PID control showed reductions of vibration magnitudes of the deflection responses for both links. Summaries of the maximum responses magnitudes for link-1 and link-2 accomplished with NN based PID control and PID control is presented in Table 2.

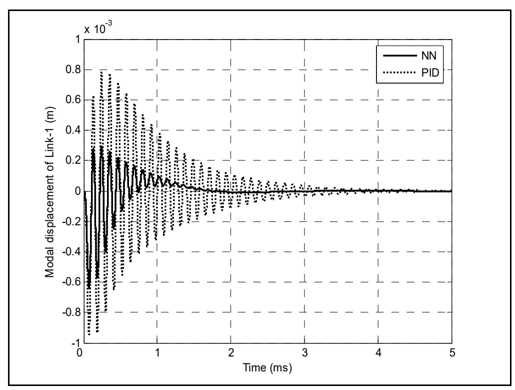

Fig.5. Deflection responses of Link-1

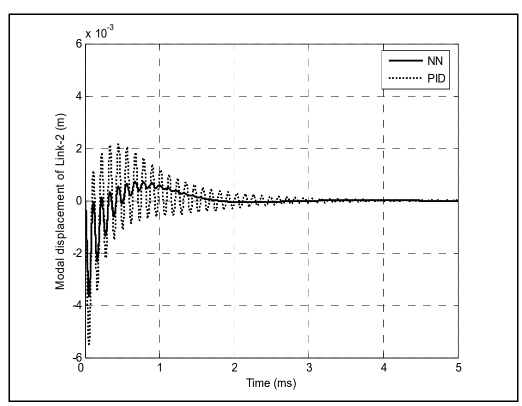

Fig.6. Deflection responses of Link-2

The end-point responses using NN based PID control and PID control with 0.3 kg payloads for link-1 and link-2 of the two-link flexible manipulator are illustrated in Figure 7 and 8. Results indicated that the acceleration increased the vibration magnitudes of the end-point for both links caused by the increasing payloads. On the other hand, there were reductions of the vibration magnitudes of the end-point acceleration for both links with NN based PID control compared with PID control. The maximum magnitudes accomplished with NN based PID control and PID control for the responses for link-1 and link-2 are portrayed in Table 2.

TABLE I. RELATION AMONG PAYLOADS, DEFLECTION AND END-POINT ACCELERATION RESPONSES

Payloads (kg)	End-point acceleration responses of the system							
	Link-1				Link-2			
	NN based PID		PID		NN based PID		PID	
Deflection (mm)	-0.72	0.12	-0.92	0.43	-1.77	0.29	-2.29	0.55
End-point acceleration (mm/s^2)	-0.04	0.03	-0.05	0.05	-0.07	0.08	-0.14	0.12

TABLE II. RELATION BETWEEN PAYLOADS AND SPECIFICATION OF ANGULAR POSITIONS

Payloads (kg)	Time responses specification of angular positions							
	Link-1				Link-2			
	Settling time (s)		Overshoot (%)		Settling time (s)		Overshoot (%)	
	NN	PID	NN	PID	NN	PID	NN	PID
0.3	1.15	1.98	2.32	13.18	1.22	2.10	1.94	11.53

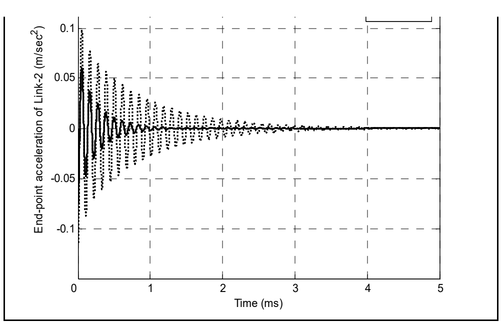

Fig.7. End-point acceleration of Link-2

A comparison of the system responses using the control schemes revealed that maximum performance in input tracking capability of the system could be achieved using NN based PID control and also PID control.

Comparisons between angular position responses of the system without payload revealed that the NN based PID had smaller overshoot and lower the settling time for both links. It generated 83 % and 81 % of overshoot reduction for link-1 and link-2 respectively compared to PID control. NN based PID control also showed lower settling time for both links with the percentages 41 % and 28 % for link-1 and link-2 respectively compared to PID control.

The comparisons between angular position responses of the system with payloads 0.3 kg also revealed similar results as the system without payload. Smaller overshoot and lower settling time for both links occurred for the NN based PID control as shown in Table 2. NN based PID control produced the overshoot decreases by 82 % and 83 % for link-1 and link-2 respectively compared with PID control with payload 0.3 kg. However, the decreases of settling time with payload 0.3 kg for both links by 42 % and 42 % for link-1 and link-2 respectively were occurred by NN based on PID control.

V. CONCLUSION

The development of a PID controller is initially conducted for control strategies of the two-link flexible manipulator with payload variations. In accordance with its universality, any nonlinear systems can apply NN based on PID controller. It is applied to control the input tracking of the two-link flexible manipulator. The control scheme performances were assessed by considering the input tracking capability of the system. Results were further compared to PID controller. The dynamic model and NN based on PID control have been simulated in particular time domain. The time domain is where the system responses that consist of positions of angular, deflection and acceleration of the end-point are analyzed. NN based on PID control demonstrates better performance as an effective technique in the area of input tracking.

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