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Research Article

Adaptive Neural-Fuzzy controller design combined with LQR to control the position of gantry crane

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ABSTRACT

As the world grows, the demand for transporting goods is increasing, the number of goods in factories and ports is increasing, to transport all these goods, cranes are indispensable. In fact, currently, crane rigs working in factories and ports operate with low stability, when working or the phenomenon of swaying of the load occurs, leading to inaccurate positioning, loss of safe transportation of goods. To overcome these shortcomings, the paper proposes the design of a neural-fuzzy adaptive controller combined with an LQR controller (ANFIS-LQR) to control the forklift's position in the shortest time to achieve the desired exact position. At the same time, we want to control the deflection angle of the load so that the vibration when working is minimal. To check and evaluate the quality and stability of the system; the proposed design controller is simulated on MATLAB/Simulink software in the case of changes in system parameters and noise affecting the gantry crane system. To evaluate the superiority of the paper compared with published works, the author compares ANFIS-LQR with other published control methods such as DE-PID, Fuzzy-PD, Fuzzy dual and Fuzzy sliding, the simulation results show that the neural-fuzzy adaptive controller combined with the proposed LQR controller works well $t_{xlvt} = 2.1s$, $t_{x\lg t} = 3.5s$, $\theta_{\max} = 0.3(rad)$.

1. Introduction

In the age of industrialization, gantry cranes play a particularly important role. Safe, efficient and timely transportation of goods is essential. Therefore, there have been many studies to improve the usability and increase the operational efficiency of gantry cranes.

Figure 1. Pictures of gantry cranes

Structurally, the overhead crane gantry is moved by the forklift and the load is suspended on the forklift via a sling [1]. Pendulum motion model [2]. These structures, such as the one shown in Figure 1. Crane gantry system with functions of moving, lifting and lowering cargo however due to the natural rotation of the load these functions will work. ineffective. The swaying of the load is caused by the moving movement of the forklift truck, the frequent changes in the length of the slings and the weight of the load, in addition to the impact of disturbances such as waves, wind and collisions... To eliminate the effects of external interference on the gantry crane system [3] propose three feedback modules that detect, compensate for positioning errors, eliminate disturbances and input shaping. to reduce load fluctuations. A new mechanism for lateral control influence [4] to prevent the swaying movement of the load. An algorithm PSO [5], DE [6] is used to adjust the optimal PID and is designed for overhead crane control with off-line control parameters. In [7] proposed an OFB control law coupling achieved

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precise positioning and effectively eliminated the rotation angle of the load. A dual PD opener controls the gantry crane system [8] where the first dimming controller controls the forklift position, and the second dimming controls the load deflections. In [9], two separate fuzzy controllers are selected to simplify the control rules and system computation. In [10], it is proposed to control gantry crane systems by combining sliding mode with fuzzy controller.

In this paper, a neural-fuzzy adaptive controller combined with an LQR controller is proposed to control the position of the gantry crane while controlling the deflection angle of the load. The design controller is tested through MATLAB/Simulink simulation with good working results.

The rest of the paper is structured as follows: Part 2 Dynamic model of gantry crane system. The design of a neural-fuzzy adaptive controller combined with an LQR controller is presented in section 3. Section 4 is describes simulation results. Section 5 is conclusion.

2. Dynamic model of crane system

A gantry crane system is shown in Figure 2 with the parameters and values given [10] as shown in Table 1. The system can be modeled as a forklift with mass M. A pendulum attached to it has a mass load, which m,l is the length of the pendulum, θ is the angle of deflection of the pendulum, $\ddot{\theta}$ is the angular velocity of the load.

According to the Lagrangian equation:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right)-\frac{\partial T}{\partial q_i}+\frac{\partial P}{\partial q_i}=Q_i \tag{1}$$

where: P is the potential energy of the system, q_i is the generalized coordinate system, i is the number of degrees of freedom of the system, Q_i is the external force, and is T the kinetic energy of the system:

$$T=\sum_{j=1}^{n}\frac{1}{2}m_j\dot{x}_j \tag{2}$$

The position of the forklift (x_M, y_M) in the inertial coordinate system is given by:

$$\begin{cases} X_M = x \\ Y_M = y \end{cases} \tag{3}$$

The position of the load (x_m, y_m) in the inertial coordinate system is given by:

$$\begin{cases} x_m = x + l\sin\theta \\ y_m = l\cos\theta \end{cases} \tag{4}$$

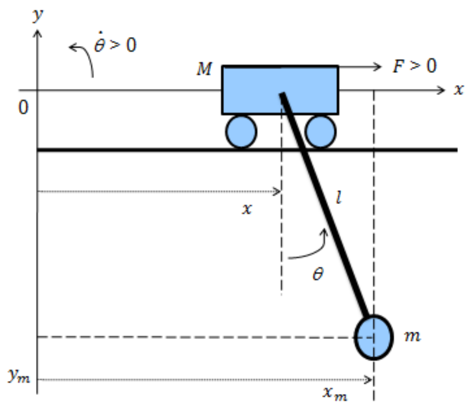

Figure 2. Diagram of the gantry crane system

From (3), (4) we have the components of the forklift's speed and the load are:

$$\begin{cases} \dot{X}_M = \dot{x} \\ \dot{X}_m = \dot{x} + l\dot{\theta}\cos\theta \end{cases} \tag{5}$$

The kinetic energy of the forklift is:

$$T_M = \frac{1}{2}M\dot{x}^2 \tag{6}$$

The kinetic energy of the load is:

$$T_m = \frac{1}{2}m\left(\dot{x}^2 + l^2\dot{\theta}^2 + 2\dot{x}l\dot{\theta}\cos\theta\right) \tag{7}$$

From (6), (7) we have the kinetic energy of the system as:

$$T = T_M + T_m = \frac{1}{2}m\dot{x}^2 + \\ +\frac{1}{2}m\left(\dot{x}^2 + l^2\dot{\theta}^2 + 2\dot{x}l\dot{\theta}\cos\theta\right) \tag{8}$$

The potential energy of the system is:

$$P = mg\left(1-\cos\theta\right) \tag{9}$$

From (8), (9) to has:

$$\frac{\partial T}{\partial \dot{x}} = M\dot{x} + m\dot{x} + ml\theta\cos\theta \tag{10}$$

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}}\right) = \left(M+m\right)\ddot{x} + ml\ddot{\theta}\cos\theta - ml\dot{\theta}^2\sin\theta \tag{11}$$

$$\frac{\partial T}{\partial x} = 0, \frac{\partial P}{\partial x} = 0 \tag{12}$$

Similar calculations (10)， (11)， (12) and instead of (1) we have the nonlinear equation of motion of the gantry crane system as follows:

$$\left(M+m\right)\ddot{x} + ml\ddot{\theta}\cos\theta - ml\dot{\theta}^2\sin\theta = F - \mu\dot{x} \tag{13}$$

$$ml\cos\theta\ddot{x} + ml^2\ddot{\theta} + mgl\sin\theta = 0 \tag{14}$$

Linearizing around the equilibrium state, then the deflection angle of the load is small, we have: $\sin\theta \approx 0, \cos\theta \approx 1, \dot{\theta}^2 \approx 0$ Since then, the nonlinear motion equation of the gantry crane system is simplified with the following linearization model:

$$\begin{aligned}(M+m)\ddot{x}+ml\ddot{\theta}&=F-\mu\dot{x}\\ \ddot{x}+l\ddot{\theta}+g\theta&=0\end{aligned} \quad (15)$$

From (14), (15) we get the following system of linear equations:

$$\begin{cases}\ddot{x}=\dfrac{gm}{M}\theta-\dfrac{\mu}{M}\dot{x}+\dfrac{1}{M}F\\ \ddot{\theta}=-\dfrac{g(M+m)}{lM}\theta+\dfrac{\mu}{lM}\dot{x}-\dfrac{1}{lM}F\end{cases} \quad (16)$$

In which: F are the external forces acting on the gantry crane system.

Table 1. Symbols and values of crane gantry parameters

Symbol	Describe	Value	Unit
M	Forklift weight	5	Kg
l	Length of load cable	1	m
m	Load mass	10	Kg
g	Gravitational constant	9.81	m/s^2
μ	Coefficient of friction	0.2	

3. Adaptive Neuro-Fuzzy inference system combined with LQR controller

The article proposes an adaptive neuron - fuzzy controller ANFIS (Adaptive Neuro-Fuzzy Inference System) [13] combined with LQR controller to control the forklift's position in the shortest time to achieve the desired position simultaneously control the deflection angle of the load so that the oscillation is minimal.

The neural-fuzzy adaptive controller combined with the LQR controller (ANFIS-LQR) is a controller in which the control device consists of the following two components: the linear control component LQR and the adaptive control component neuron- fuzzy. The neural-fuzzy adaptive controller combined with the LQR controller can be set up based on the signals as error e(t) and derivative e'(t). The neural-fuzzy adaptive controller has the ability to learn and control adaptively when the system parameters change and has very good characteristics in the large deviation region, its nonlinear characteristics can generate dynamic responses very fast. When the process of the system approaches the set point (error e(t) and its derivative e'(t) is approximately equal to 0) the role of the neural-fuzzy adaptive controller is limited, so the controller will work with LQR regulator.

The schematic diagram of the neural-fuzzy adaptive controller ANFIS combined with the LQR controller for the gantry crane system is shown in Figure 3.

3.1. Design of the LQR controller

The gantry crane system is described by the following system of state equations:

$$\begin{cases}\dot{x}(t)=Ax(t)+Bu(t)\\ y(t)=Cx(t)+Du(t)\end{cases} \quad (18)$$

Where: $x=\begin{bmatrix}x & \dot{x} & \theta & \dot{\theta}\end{bmatrix}^T$ is a state variable representing the displacement of the forklift, the velocity of the forklift, the deflection angle and the angular velocity of the load. $u(t)=F$ is the input variable.

$$A=\begin{bmatrix}0 & 1 & 0 & 0\\ 0 & -\dfrac{\mu}{M} & \dfrac{gm}{M} & 0\\ 0 & 0 & 0 & 1\\ 0 & \dfrac{\mu}{lM} & -\dfrac{g(M+m)}{lM} & 0\end{bmatrix}, B=\begin{bmatrix}0\\ \dfrac{1}{M}\\ 0\\ -\dfrac{1}{lM}\end{bmatrix}$$

$$C=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}, D=\begin{bmatrix}0\\ 0\end{bmatrix}$$

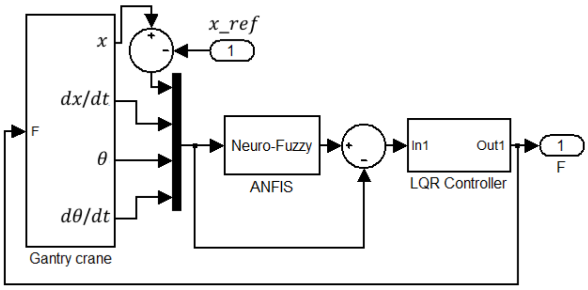

Figure 3. Schematic diagram of matlab structure of ANFIS-LQR

The performance of the system is according to the best J index [11]. The overall quality criteria are:

$$J=\frac{1}{2}\int_0^{\infty}(x^TQx+u^TRu)d(t) \quad (19)$$

Where: $Q=Q^T$ is a positive semi deterministic matrix, $R=R^T$ is a positive definite matrix.

The optimal control signal u is:

$$u(t)=-Kx(t), K=R^{-1}B^TP \quad (20)$$

Where P is the positive semi-definite solution of the Ricatti algebraic equation:

$$PA+A^TP-PBR^{-1}P+Q=0 \quad (21)$$

Solving equation (21) we get the value P, from which the value of K.

Therefore, when designing the LQR controller, it is important to choose the appropriate weight matrix from which to determine the optimal feedback matrix.

By trial and error method, the authors choose the weight matrix as follows: R = 1.

$$Q=C'\text{x}\,C=diag(Q_{1,1},\ 0,\ Q_{3,3},\ 0) \quad (22)$$

In which: The weight position of the forklift is selected as $Q_{1,1}$ = 1000, the weight angle of the load is $Q_{3,3}$ = 500.

The MATLAB Toolbox software provides a function that can be used to design optimally linearly tuned squares [12]. The LQR feedback matrix is calculated as follows.

$$K = LQR(A,B,Q,R) \qquad (23)$$

$$K = [31,6228;\ 14,4553;\ \text{-}15,650;\ 0,5413]$$

The LQR controller for the gantry crane system is shown in Figure 4.

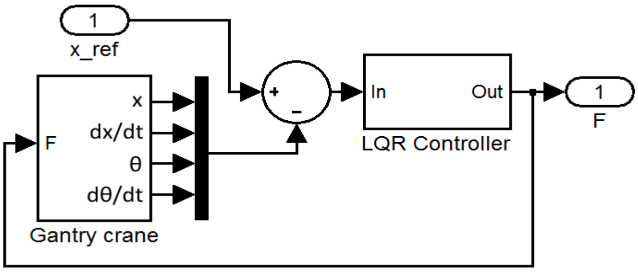

Figure 4. Diagram of matlab structure of LQR controller for gantry crane system

3.2. Design of the neural-fuzzy adaptive controller ANFIS

3.2.1. A general introduction to the neural-fuzzy adaptive controller ANFIS

The ANFIS Fuzzy Adaptive Neural Controller is an application that runs on MATLAB software. The network provides methods so that the neural-fuzzy system can learn from given input/output information (training information). Specifically, in this article, the authors have conducted for the ANFIS neural-fuzzy adaptive controller to learn from the LQR controller, thereby building a system of membership functions that allows this system to infer The system output response from input stimuli is based on the structure of the learned system. ANFIS uses least squares estimation and error back-propagation in the direction of decreasing gradient to build membership function parameters. The basic computation in fuzzy systems (FIS) is considered as a parameterized nonlinear map described by the function *f* as follows:

$$f(x) = \frac{\sum_{l=1}^{m} y^l \left(\prod_{i=1}^{n} \mu_{A_i^l}(x_i)\right)}{\sum_{i=1}^{m} \left(\prod_{i=1}^{n} \mu_{A_i^l}(x_i)\right)} \qquad (24)$$

Where: y^l is the output, $\mu_{A_i^l}$ is the membership function of the input corresponding to the composition rule *l*. The Max-PROD composition rule and the defuzzification method are the focus point methods.

3.2.2. Design steps of neural-fuzzy adaptive controller for gantry crane system

Step 1. Design the matlab structure diagram for the ANFIS controller that learns according to the LQR controller as shown in Figure 5.

Where: *x1, x2, x3, x4, u* are the position, velocity of the forklift, the deflection angle, the angular velocity of the load and the control signal, respectively.

Step 2. Perform with a sampling period of 0.01s and run for 10s, we will have 1000 samples similar to 10 samples in Table 2.

Step 3. Training the neural-fuzzy network ANFIS on MATLAB software.

- First, load the training data into the workspace of the ANFIS GUI editor. Then we have a diagram of the data to be trained as a set of circles as shown in Figure 6 .

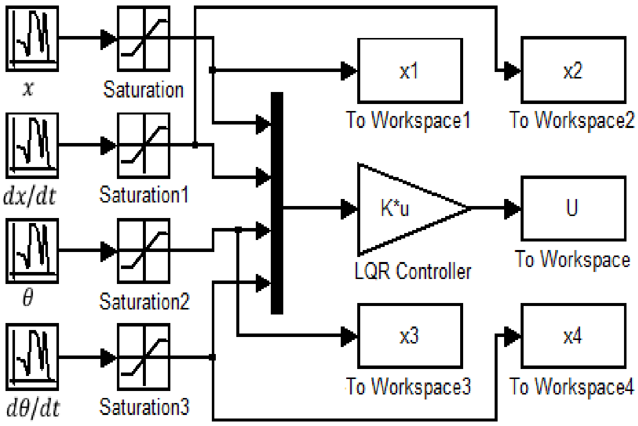

Figure 5. Structure diagram of matlab for ANFIS controller sampling LQR controller

Table 2. Sample x_1, x_2, x_3, x_4, u to train the ANFIS network

x1	x2	x3	x4	u
-0,5946	-6,2273	0,2959	30,000	-97,212
-3,0000	-20,204	-0,5600	-6,2687	-381,56
0,2001	1,6384	-0,1222	30,000	48,162
-1,8985	12.096	0,3767	-29,933	92,727
-0,9562	1.2494	-0,1653	30,000	6,6477
-1,1274	-1.4226	-0,1752	-30,000	-69,712
-2,5769	16.047	0,1406	-30,000	132,03
-1,4476	3.4685	-0,6441	30,000	30,679
-1,4191	-13.786	0,1855	30,000	-230,83
-2,0096	8.6680	-0,3196	30,000	82,989

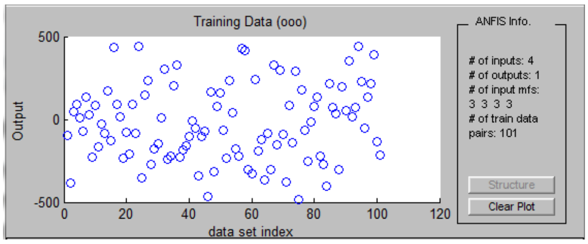

Figure 6. Diagram of data to be trained

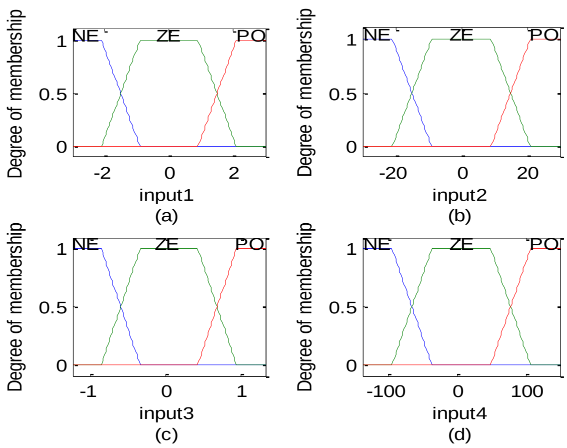

Figure 7. The membership functions of the input and output variables of the fuzzy controller

- Second, we proceed to choose Generate FIS with the input membership functions using 3 fuzzy sets to describe, the membership functions have trapmf form, the output is linear and the range of input language variables, The output is shown in Figure 7. From the input, output and member functions to describe the variables, a total of 3^4 = 81 fuzzy rules are used to control the gantry crane system. In which fuzzy rules from 1 to 11 are given as shown in Figure 8. The spatial fuzzy controller's input - output relationship is shown in Figure 9.

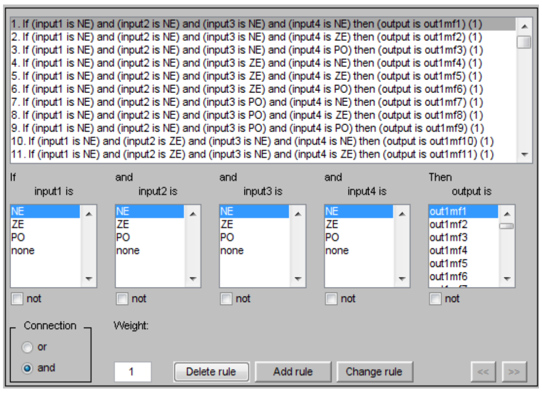

Figure 8. Fuzzy rule IF-THEN of fuzzy controller

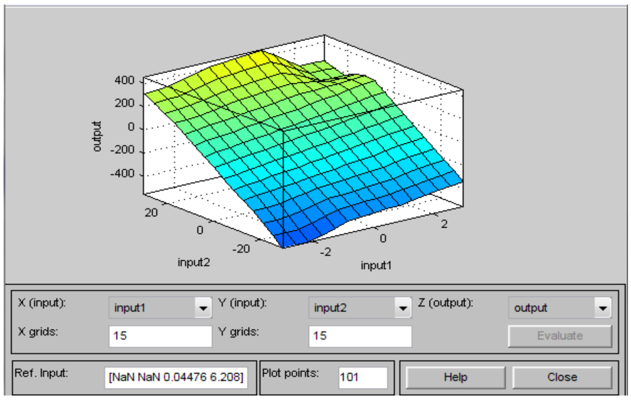

Figure 9. The windows for input - output relationship of fuzzy controller in space

- Thirdly, we proceed to select Epochs, then for training the ANFIS network, we get an error-free diagram as shown in Figure 10.

Step 4. Design the matlab structure diagram for the neural-fuzzy adaptive controller ANFIS to control the gantry crane system as shown in Figure 11.

Step 5. System Optimization: Simulate the system to check the results.

4. Simulation results

The designed controller is simulated on MATLAB/Simulink software. The system parameters used for simulation are shown in Table 1. The results of comparing the control signal of the ANFIS controller learning according to the LQR controller with the control signal of the LQR controller are shown in Figure 11.

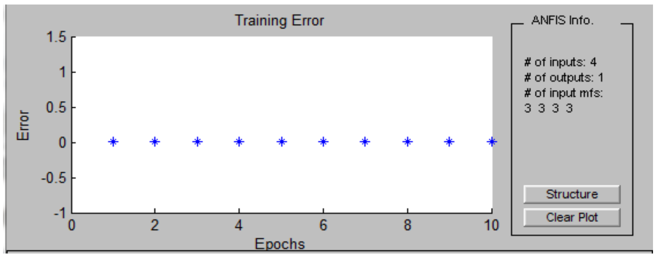

Figure 10. Diagram of the trained data of the ANFIS network

In which: The green characteristic line is the control signal of the LQR controller, the blue characteristic line is the control signal of the ANFIS controller. It can be seen that the ANFIS controller has learned well the control signal of the LQR controller.

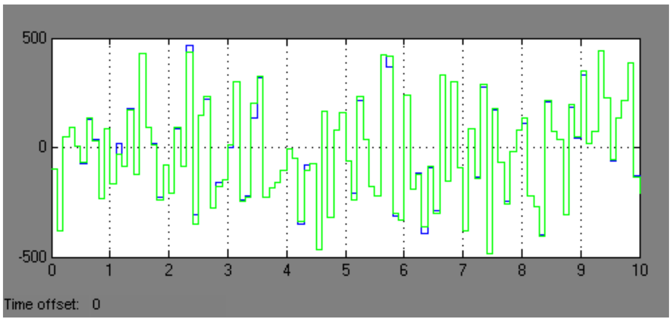

Figure 11. Control signal of ANFIS controller and LQR controller

Simulate the system with the desired forklift position x_ref=0.5m . The simulation results are shown in Figure 12. In which: x-LQR, θ-LQR are the characteristic curves of the response of the forklift's position and the load deflection angle when controlled by the LQR controller, respectively. For forklift position with overcorrection POT=5%, setting error $e_{xl} = 0\%$, position setting time $t_{xlvt} = 3.1s$, and for load deflection angle with the largest angle $\theta_{max} = 0.3$ (rad) and setting time of deviation angle $t_{x\lg t} = 3.1s$; x-ANFIS, θ - ANFIS is the characteristic curve that responds to the forklift's position and the load deflection angle when controlled by the ANFIS controller with POT = 5%, $e_{xl} = 0\%$, $t_{xlvt} = 3s$, $\theta_{max} = 0.3$ (rad) and $t_{x\lg t} = 3.1s$; x-ANFIS-LQR, θ - ANFIS-LQR respectively is the characteristic curve of response of forklift position and load deflection angle when controlled by ANFIS-LQR controller with POT = 0%, $e_{xl} = 0\%$, $t_{xlvt} = 2.1s$, $\theta_{max} = 0.3$ (rad) and $t_{x\lg t} = 3.5s$.

By comparing the results when using the controllers, it can be seen that the controllers all achieve good control performance. But the use case of the ANFIS-LQR controller has stronger adaptability and better control quality because overshoot is no longer present and accurate position is achieved in less time

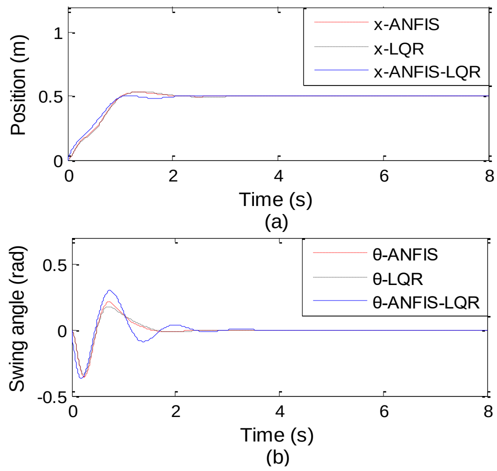

Figure 12. Characteristic curve: a) response to forklift position, b) load deflection angle

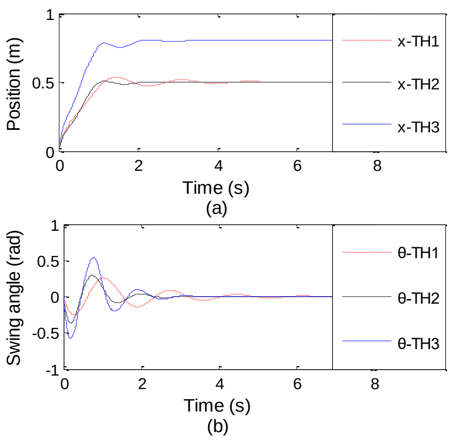

Figure 13. The characteristic curve: a) of the response of the forklift position, b) the deflection angle of the load when changing system parameters

In order to keep abreast with the actual situation and study the impact of the controllers, we in turn change the specific parameters as follows: Case 1 (TH1) increases l = 0.61m, other parameters remain unchanged. Case 2 (TH2) increased m=1.6kg, other parameters remained unchanged. Case 3 (TH3) increased by $x_{\_ref} = 0.8m$, other parameters remained unchanged.

Simulate the system on MATLAB/Simulink software for the above three cases. The simulation results are shown in Figure 13. It can be seen that when the system parameters change in the case of using ANFIS-LQR, the gantry crane system still achieves accurate position in a short time and control. small load deflection angle.

In addition, when the gantry crane system is in operation, there are external noises acting on the system to test the reliability of the controllers [9]. The specific crane gantry system is as follows: TH1 is noise causing the load to fluctuate with the noise signal step assumed as follows: Step time = 4s, deviation angle = 0.2 (rad), time = 1 second. TH2 is noise that changes cart position with noise signal step assumed as follows: Step time = 1s, range = 0.2m, time = 1s; The simulation results are shown in Figure 14. TH3 noise signal acting on the system has the form as shown in Figure 15, then the response curve of the forklift's position and the load deflection angle is shown as shown in Figure 16.

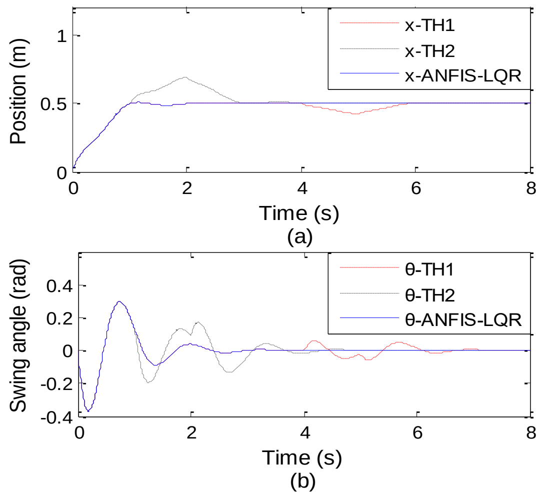

Figure 14. Response curve: a) of forklift position, b) load deflection in the presence of noise

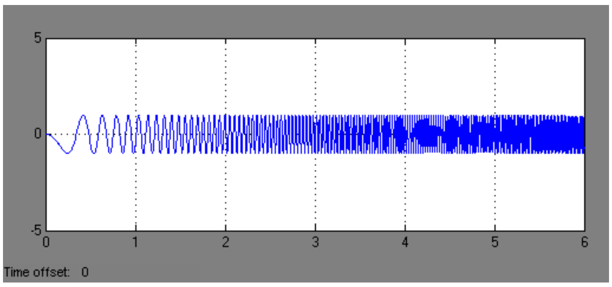

Figure 15. The characteristic curve of the noise signal that affects the system

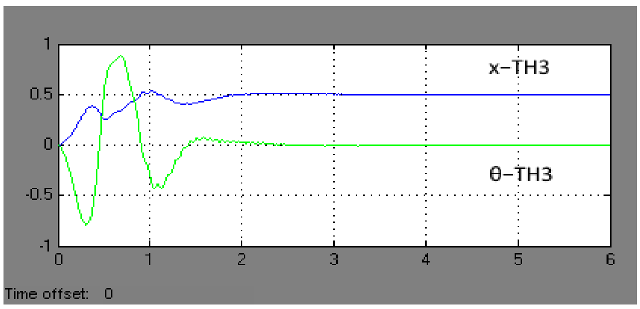

Figure 16. Response curve of forklift position and load deflection in the presence of TH3 noise

Table 3. Comparison of ANFIS-LQR with other published control methods

Symbol	ANFIS - LQR	DE-PID [6]	Fuzzy-PD [8]	Fuzzy dual [9]	Fuzzy-Sliding [10]
x_ref	0,5m	5m	0.2m	1m	2m
POT	0%	3%	0%	13%	0%
e_{xl}	0%	0%	0%	0%	0%
t_{xlvt}	2,1s	12s	4,5s	35s	12.5s
$t_{x\lg t}$	3,5s	25s	3,5s	26s	13s
$\theta_{\max}$	0,3 rad	0.65 rad	0,06 rad	0,02 rad	0,3 rad
$\theta_{\min}$	0 rad	0 rad	0 rad	0 rad	0 rad

It can be seen that in the presence of disturbances, the system can still achieve the desired position in a short time and control the deflection angle of the small load.

To clarify the superiority of the solution, the authors compared the ANFIS-LQR controller with other published control methods as shown in Table 3.

Based on the results in Table 3, it can be seen that with the crane gantry object that the authors studied in [10], using the ANFIS-LQR controller is the most optimal.

5. Conclusion

In this paper, we designed the ANFIS-LQR controller to control the position of the forklift in a short time to reach the desired position while controlling the deflection angle of the small load. The ANFIS-LQR controller is tested through MATLAB/Simulink simulation, the simulation results when changing system parameters and checking the reliability of the control system by introducing the noise signal step into the system. The system shows that the gantry crane moves to the desired position quickly in about $t_{xlvt} = 2.1s$ while controlling the vibration of small loads with $\theta_{\max} = 0.3\,(\text{rad})$. In addition, the ANFIS-LQR controller is compared with other control methods the author compares such as DE-PID, Fuzzy-PD, Fuzzy dual and Fuzzy sliding, the simulation results show that the neural-fuzzy adaptive controller combined with the proposed LQR controller works well. As a result, the proposed ANFIS-LQR controller to control the gantry crane is the most optimal.

Author's Note

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References

[1] J. Smoczek, Interval arithmetic-based fuzzy discrete-time crane control scheme design, Bull. Pol. Ac.: Tech. 61 (4), 2013, pp. 863–870.

[2] N. Sun, Y.C. Fang, and X.B. Zhang, *Energy coupling output feedback control of 4-DOF underactuated cranes with saturated inputs,* Automatica 49 (5), 2013, pp. 1318–1325.

[3] Khalid L. Sorensen, William Singhose, Stephen Dickerson, *A controller enabling precise positioning and sway reduction in bridge and gantry cranes,* Control Engineering Practice 15, 2007, pp. 825–837.

[4] Quang Hieu Ngo and Keum-Shik Hong, *Sliding-Mode Antisway Control of an Offshore Container Crane,* IEEE/ASME Transactions on Mechatronics, VOL. 17, NO. 2, APRI, 2012.

[5] Mohammad Javad Maghsoudi, Z. Mohamed, A.R. Husain, M.O. Tokhi, *An optimal performance control scheme for a 3D crane,* Mechanical Systems and Signal Processing 66-67, 2016,pp. 756–768.

[6] Zhe Sun, Ning Wang, Yunrui Bi, Jinhui Zhao, *A DE based PID controller for two dimensional overhead crane*, Proceedings of the 34th Chinese Control Conference July 28-30, 2015, Hangzhou, China.

[7] Ning Sun, Yongchun Fang, Xuebo Zhang, *Energy coupling output feedback control of 4-DOF underactuated cranes with saturated inputs*, Automatica 49, 2013, pp. 1318–1325.

[8] Naif B. Almutairi and Mohamed Zribi, *Fuzzy Controllers for a Gantry Crane System with Experimental Verifications, Article in Mathematical Problems in Engineering*, 2016, DOI: 10.1155/1965923.

[9] Lifu Wang, Hongbo Zhang, Zhi Kong, *Anti-swing Control of Overhead Crane Based on Double Fuzzy Controllers*, IEEE Chinese Control and Decision Conference (CCDC), 2015, 978-1-4799-7016-2/15/$31.00.

[10] Dianwei Qian, Jianqiang Yi, Dongbin Zhao, *Control of Overhead Crane Systems by Combining Sliding Mode with Fuzzy Regulator*, Milano (Italy) August 28 - September 2, 2011.

[11] Yu Zhangguan, *Modern Control Theory [M]*, Harbin: Harbin Institute of Technology Press, 2005.

[12] Xue Dingyu, Chen Yangquan, *System Simulation Technology and Application Based on MATLAB / Simulink [M]*, Beijing, 2009.

[13] Dervis Karaboga & Ebubekir Kaya, *Adaptive network based fuzzy inference system (ANFIS) training approaches: a comprehensive survey*, An International Science and Engineering Journal, 2019