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Neuro-fuzzy-based anti-swing control of automatic tower crane

Saleh B. Al-Tuhaifi, Kasim Mousa Al-Aubidy
Mechatronics Engineering Department, Faculty of Engineering and Technology, Philadelphia University, Amman, Jordan

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ABSTRACT

Controlling the position of the final load and the anti-swing control of the loads during the operation of the tower crane are challenging tasks. These are the most important control issues for safe operation, which are difficult to achieve easily with conventional control systems. Hence, the need to integrate the concepts of soft-computing into the tower crane control system. The aim of this research work is to design an adaptive-network-based fuzzy inference system (ANFIS) controller to move the payload to the final position with the lowest possible swing angle. To evaluate the ability of the proposed controller to meet the control requirements, its performance was compared to three other controllers: a conventional proportional derivative (PD) controller, a fuzzy-tuned PD controller and a fuzzy controller. MATLAB-based computer simulations of the crane and controllers were carried out to verify and compare the performance of the proposed controllers. The obtained results show the effectiveness of the ANFIS-based controller in adjusting the load position while keeping the load fluctuations small at the final position. The load oscillation angle is about ±2.28° with the ANFIS controller while it is about ±10° when using the PD controller. In addition, only one ANFIS controller is used for both load position and swing angle control.

Corresponding Author:

Kasim Mousa Al-Aubidy
Mechatronics Engineering Department, Faculty of Engineering and Technology
Philadelphia University, Amman, Jordan
Email: kma@philadelphia.edu.jo

1. INTRODUCTION

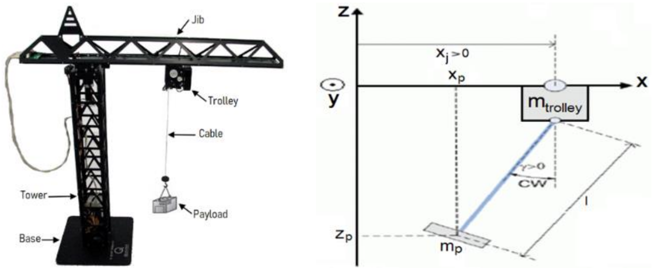
Tower cranes are widely used in factories, ports and high building constructions to lift heavy goods to great heights, or to move them from one place to another. Crane control systems are a vital area of scientific research and need more studies and research works, especially with the development of computer and communication technologies. They have worked to develop control systems for cranes that have the ability to move the load as quickly as possible and keeping the swing angle as small as possible in the final position [1]. On the other hand, the crane needs a skilled operator who has the ability to handle the control system easily in order to move the payload and prevent it from swinging. Swing motion can be reduced by decreasing the trolley speed and this leads to a decrease in productivity [2]. Therefore, many studies have focused on the development of anti-swing control systems for tower crane [3]. Some have used open-loop control strategies, including input shaping [4], filtering [5], and command smoothing [6], while others have suggested closed-loop control strategies. There are several control strategies used for crane control including linear control [7], model predictive control [8], adaptive control [9], sliding mode control [10], [11], proportional integral derivative (PID) controllers [12], gain scheduling control [2] and others [13]. These control methods need an accurate mathematical model of the lever in order to derive the required controller, and the parameters of the controller need to be updated due to the dynamics of the lever [12], [14]. Obtaining the exact mathematical model of the tower crane, which simulates its operation with changing weight, load shape and wind speed, is not an easy task and requires an online update. The design of most traditional controllers depend on the mathematical model of the tower crane, and because of the simplification of these models, the performance of these controllers was not as expected due to the dynamics of the crane. Recently, most studies and research have been directed towards incorporating artificial intelligence (AI) concepts into control systems to improve the performance of tower cranes [14]. Therefore, intelligent control systems appeared that used fuzzy logic [15], [16], or neural networks [17], [18] as well as genetic algorithms [19]. Selma *et al.* [14] and Benhellal *et al.* [20] have used a combination of fuzzy logic and neural networks, or a combination of neural networks and genetic algorithms [21], [22] to improve the performance of the control system. Moreover, soft-computing tools, such as fuzzy logic, were also used to online tuning of the PID controller parameters without the need for a lever mathematical model [23], [24].

The main objective of this paper is to drive the jib and trolley of the tower crane from the initial position to the final position with an acceptable speed and high accuracy so that the swing angle is as low as possible. An adaptive-network-based fuzzy inference system (ANFIS)-based controller for a tower crane is proposed in this paper. The performance of the ANFIS-based controller is compared with three controllers; a conventional proportional derivative (PD) controller, a fuzzy-tuned PD controller, and a fuzzy logic controller. The rest of the paper is organized as; the structure and mathematical model of a tower crane are described in section 2. Control methods are discussed in section 3. The design of an ANFIS-based controller is given in section 4. Simulation and comparison results are discussed in section 5. Finally, the conclusion and some proposed future work are presented in section 6.

2. MATHEMATICAL MODEL OF TOWER CRANE

A real tower crane is a complex structure that includes the base, mast, boom, balance beams, trolley and control systems. In this paper, an educational crane of type “Quanser 3 DOF” was used, as shown in Figure 1. It is a compact version of the tower crane, as illustrated in Figure 1(a), has three degrees of freedom; the tower rotates in both directions, the trolley moves along the horizontal segment, and the height of the load can be changed. The jib rotates clockwise and counterclockwise and has a trolley moving along the jib using a motor. The trolley has a cable to lift the load up or down using another motor. Three motors are driven by electronic drive units and optical sensors to measure position and speed [25]. There are many ways to obtain a mathematical model of a tower crane, including the use of finite element analysis and Lagrangian methods [1], [26]. In order to obtain an accurate dynamic model representing the tower crane systems, several parameters have to be included when deriving the mathematical model. Such a model is a set of nonlinear equations, and it is difficult to use it for controller design or for performance analysis because the computation would be too complex. In fact, several assumptions are made to simplify the obtained model. For example, some mathematical models have included sensors and actuators, while some studies and research do not. In general, the mathematical model of tower crane appears nonlinear. Thus, it is easier to implement linearization to get an approximate linear model.

The jib rotates in a horizontal plane and carries a trolley that moves radially. The trolley carries the load through a variable length (l) cable. The loading position above any point in the workplace is handled by the combined movements of both the trolley and the jib. In fact, the jib system model is similar to the inverted pendulum model, as illustrated in Figure 1(b), where:
- X: the horizontal axis along which the cart moves
- Z: the vertical axis along which the tower rotates
- α: the rotation angle about the x-axis
- ɤ: the rotation angle about the y-axis
- θ: the rotation angle about the z-axis



(a) (b)

Figure 1. Quanser 3 DOF tower crane layout [25]: (a) crane layout and (b) free body diagram

The jib is modeled as a two-dimensional linear gantry by assuming the payload is at a fixed height and is fixed about the gimble angle (α), and the movement is perpendicular to the jib length. In other words, it is assumed the payload rotates only about gimble angle (Υ). The mathematical model of the tower crane is a nonlinear system, so the Lagrange method is used to find the nonlinear dynamics of the crane. The following equations are used to obtain the state space matrices [25].

$$\dot{\mathrm{x}} = A \times x + B \times u \text{ and } y = C \times x + D \times u \tag{1}$$

Where:

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{m_p\, r_{j.pulley}{}^2\, g}{m_{trolley}\, r_{j.pulley}{}^2 + J\psi\, K_{g.j}{}^2} & 0 & 0 \\ 0 & -\frac{g(m_{trolley}\, r_{j.pulley}{}^2 + m_p\, r_{j.pulley}{}^2 + J\psi K_{g.j}{}^2}{(m_{trolley}\, r_{j.pulley}{}^2 + J\psi\, K_{g.j}{}^2) l_p} & 0 & 0 \end{bmatrix} \tag{2}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ \frac{r_{j.pulley}\, \eta_{g.j}\, K_{g.j}\, \eta_{m.j}\, K_{t.j}}{m_{trolley}\, r_{j.pulley}{}^2 + J\psi K_{g.j}{}^2} \\ \frac{r_{j.pulley}\, \eta_{g.j}\, K_{g.j}\, \eta_{m.j}\, K_{t.j}}{(m_{trolley}\, r_{j.pulley}{}^2 + J\psi K_{g.j}{}^2) l_p} \end{bmatrix} \tag{3}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \; D = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{4}$$

Where:

- $\eta_{m.j}$: jib motor efficiency
- $K_{t.j}$: jib cart motor torque constant (before gear ratio)
- $K_{g.j}$: cart motor gearbox gear ratio
- $\eta_{g.j}$: cart motor gearbox efficiency
- $r_{j.pulley}$: radius of trolley pulley from pivot to end of tooth
- $m_{trolley}$: mass of trolley
- l_p: vertical distance of payload from jib arm
- J_{psi}: jib motor equivalent moment of inertia

Then, the transfer functions of the given tower crane are given by [25].

$$\frac{x(s)}{I(s)} = \frac{18.25s^2 + 207.3}{s^4 + 13.33s^2} \tag{5}$$

$$\frac{\Upsilon(s)}{I(s)} = \frac{21.13}{s^2 + 13.33} \tag{6}$$

3. METHODS OF CONTROL

Tower cranes are responsible for lifting and transporting goods in many areas, and their work can be divided into three types: lifting the load, moving the trolley and meanwhile rotating the jib, and placing the load. However, with the movement of the jib and the trolley, the phenomenon of load oscillation appears and has become a problem that must be solved. Therefore, tower cranes are considered a non-linear system. A closed loop control system is required to control both the position (X_0) and swing angle (Υ), as shown in Figure 2. In this paper, an ANFIS-based intelligent controller is designed and implemented to move the load as quickly as possible and keep the swing angle as small as possible in the end position. In order to ensure the efficiency of the proposed intelligent controller and its ability to meet the required control requirements, a comparison was made with three well known controllers: a conventional proportional PD controller, fuzzy-tuned PD controller, and a fuzzy logic controller.

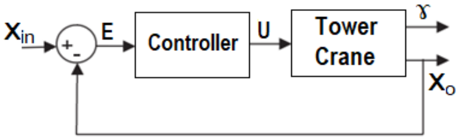


Figure 2. General layout of crane control system

3.1. Conventional PD controller

The conventional PID controller is one of the most widely used linear control technologies in crane control systems. The main problem of this controller is the continuous updating of its parameters, which are mainly based on the mathematical model of the crane. The parameters of the PID controller can also be updated using intelligent algorithms that do not depend entirely on the mathematical model of the crane. For the mathematical model obtained for the tower crane used in this research, the PD controller is sufficient to meet the required control requirements. Figure 3 shows a simulation of both the tower crane and the PD controller model. The parameter values for K_p and K_d of the controller were well chosen to obtain the best response. The main disadvantage of this controller is the real-time tuning of the parameters of the controller that depends on the dynamics of the crane.

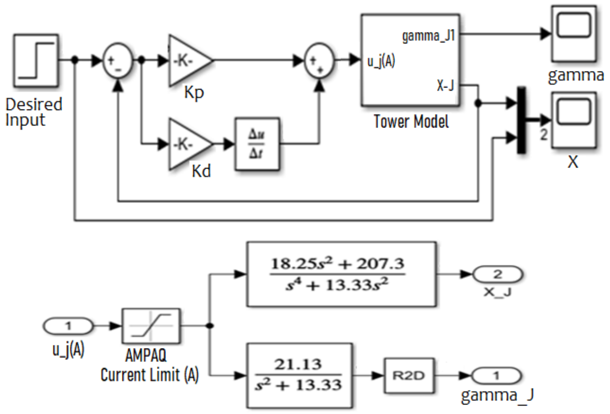


Figure 3. Simulation block diagram of a conventional PD controller

3.2. Fuzzy-tuned PD control

Several attempts have proposed new methods for self-tuning of PID controller parameters based on the mathematical model of the crane and others using intelligent algorithms. In this paper, a fuzzy tuner was used to adjust the parameters of the PD controller according to the error (E) and error change (CE), as shown in Figure 4. Two inputs have been applied to the fuzzy tuner; the error, calculated by comparing the reference input with the actual output, and the CE. The input variables (E and CE) are represented by seven fuzzy sets, while the output variables (K_p and K_d) are represented by three fuzzy sets, as shown in Figure 5. There are 49 fuzzy rules, as given in Table 1, used by the fuzzy inference engine to determine the updated values of controller parameters. The simulation of the tower crane and the fuzzy-tuned PD controller is given in Figure 6.

Table 1. Rules for fuzzy tuned PD controller

		Error (E)							Error (E)						
		NB	NM	NS	Z	PS	PM	PB	NB	NM	NS	Z	PS	PM	PB
Change error (CE)	NB	P	Z	N	N	N	Z	P	N	P	P	N	P	P	N
	NS	P	P	Z	N	Z	P	P	N	Z	P	P	P	Z	N
	NM	P	P	Z	N	Z	P	P	N	N	Z	P	Z	N	N
	Z	P	P	P	Z	P	P	P	N	N	N	Z	N	N	N
	PS	P	P	Z	N	Z	P	P	N	N	Z	P	Z	N	N
	PM	P	P	Z	N	Z	P	P	N	Z	P	P	P	Z	N
	PB	P	Z	N	N	P	Z	P	N	P	P	P	N	P	N
		(a) K_p rules							(b) K_d rules						

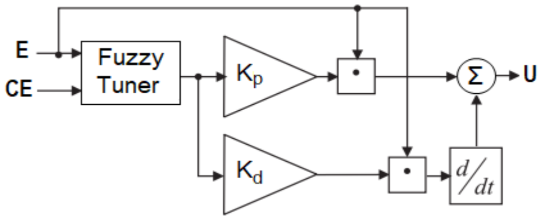


Figure 4. Structure of fuzzy-tuned PD controller

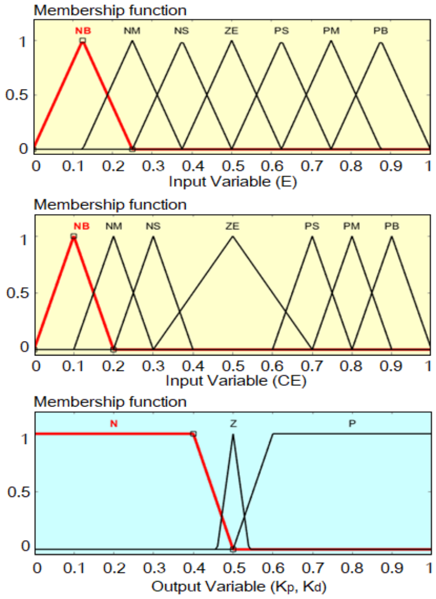


Figure 5. Membership function of input and output variables for fuzzy tuned PD controller

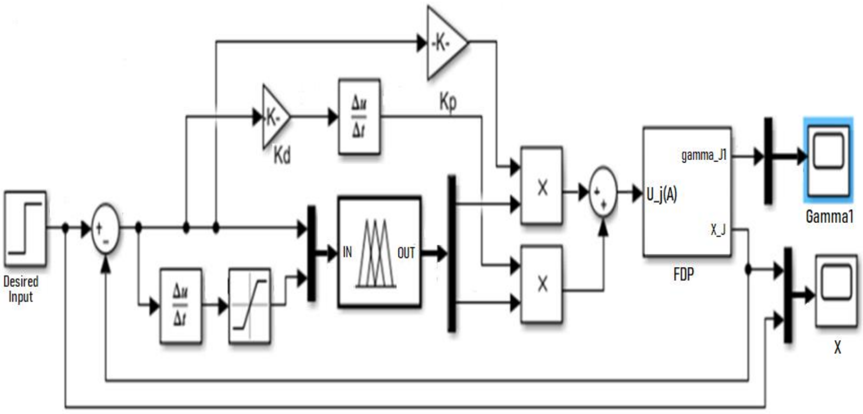


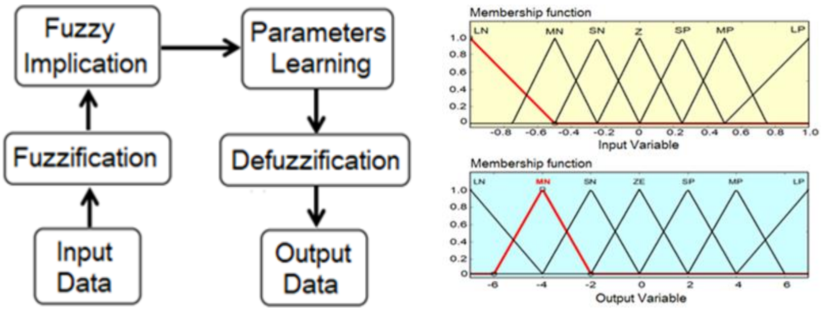
Figure 6. Simulation block diagram of fuzzy tuner of PD controller

3.3. Fuzzy controller

A fuzzy logic controller (FLC) has been used to compute the required actuating signal (U) according to the error and error change. Figure 7 shows fuzzy set controller elements in Figure 7(a) and input and output variables in Figure 7(b). Each variable is coded by seven fuzzy sets; large negative (LN), medium negative (MN), small negative (SN), zero (Z), small positive (SP), medium positive (MP), and large positive (LP), as shown in Figure 8. The implemented fuzzy controller is in fact a collection of 49 linguistic rules, as given in Table 2, which describe the relationships between inputs (E and CE), and output (U). The Mamdani style inference was used, as well as the center-of-gravity defuzzification method to convert the fuzzy output into a crisp value.

Table 2. Rules for fuzzy controller

		Error (E)						
		LN	MN	SN	Z	SP	MP	LP
Error change (CE)	LN	LN	MN	MN	MN	SN	Z	SP
	MN	LN	MN	SN	SN	SN	Z	SP
	SN	LN	MN	SN	SN	Z	SP	MP
	Z	MN	SN	SN	Z	SP	SP	MP
	SP	MN	SN	Z	SP	SP	MP	LP
	MP	SN	Z	SP	SP	SP	MP	LP
	LP	SN	Z	SP	MP	MP	MP	LP



(a) (b)

Figure 7. Fuzzy controller layout and fuzzy sets: (a) fuzzy controller elements dan (b) fuzzy sets for input/output variables

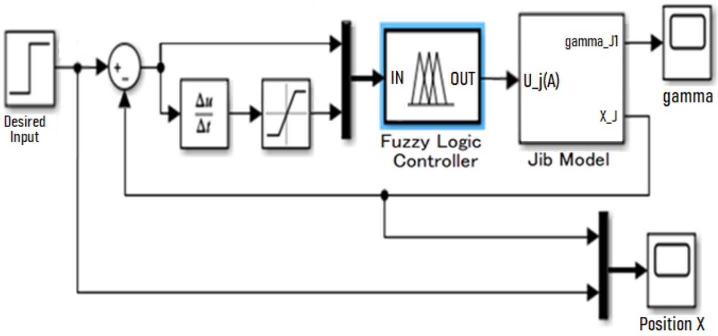


Figure 8. Simulation block diagram of fuzzy controller

4. ANFIS-BASED CONTROLLER DESIGN

An adaptive network based fuzzy inference system is a fuzzy inference system implemented within the framework of adaptive networks. ANFIS combines the advantages of both neural networks and fuzzy logic into a single framework. It is an approach that has a (non-linear) mapping defined using fuzzy if-then rules. The operation of ANFIS can be expressed as linguistic fuzzy expressions and the learning schemes of NNs are used to learn controller parameters. The ANFIS controller is widely used to control the non-linear system. Since the tower crane is a non-linear system, ANFIS was adopted in this paper to control both the payload position (X_0) and the swing angle (γ).

The proposed ANFIS controller is used to create an input-output mapping based on a set of fuzzy if-then rules and input-output data pairs to control both the position (X_0) and swing angle (γ). It combines the ability of rule-based fuzzy controller and the learning ability of a neural network to improve the membership functions of fuzzy sets. The ANFIS model architecture, as shown in Figure 9, consists of two parts; the condition part and the conclusion part, which are linked to each other by rules in the form of a multi-layer neural network. The first layer has 14 nodes to execute the fuzzification process. The second layer has 49 nodes to implement the fuzzy and operation of the condition part of the fuzzy rules. The third layer has 49 nodes to normalize the membership functions. The fourth layer is a single node that executes the conclusion part of the fuzzy rules, and finally the fifth layer is a single node to compute the output of fuzzy system by summing up the outputs of previous layer. Figure 9 outlines the main six steps of the implemented ANFIS controller.

- Step 1. Input data: the 441 pairs of input data will be divided into three sets: training data (272 pairs), testing data (85 pairs), and validation data (84 pairs).
- Step 2. Fuzzification: the crisp input variables are transformed into fuzzy sets. In this case, the number of fuzzy sets and the shape of the membership functions must be chosen carefully.
- Step 3. Fuzzy implication: in this step the structure and fuzzy rules of ANFIS are determined.
- Step 4. Parameters learning: adjustment of weights and modification of input/output membership functions using least square error and backpropagation from the training dataset and the testing dataset. Figure 10 shows training data for ANFIS with 1000 iterations (epochs).
- Step 5. Defuzzification: this process maps a fuzzy set output to a crisp set output.
- Step 6. Output data: the generated control signal is transferred to the actuating element of the tower crane.

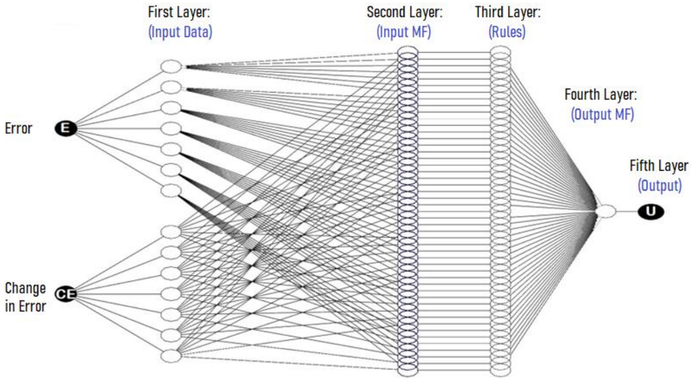


Figure 9. ANFIS model structure

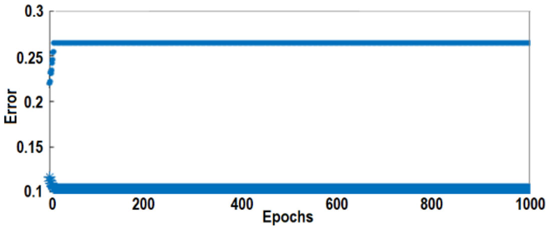


Figure 10. Training data for ANFIS controller

5. RESULTS AND DISCUSSIONS

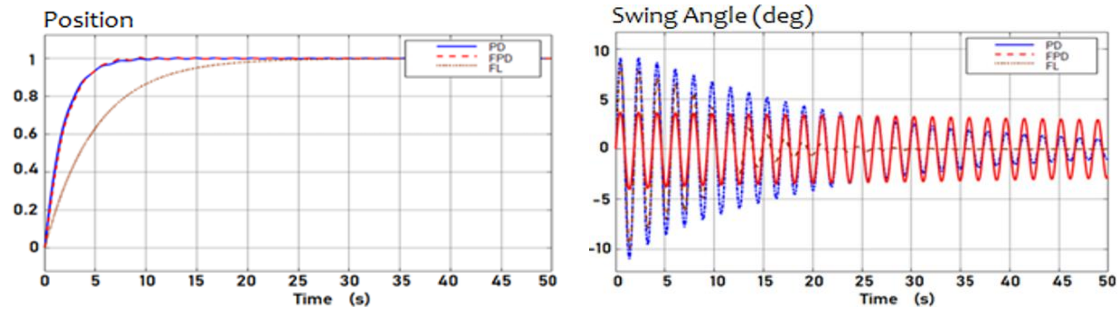
Several tests were carried out on the proposed ANFIS controller to verify its efficiency in controlling the payload position and swing angle of the tower crane. The main reason for using the ANFIS controller is that it does not need the exact mathematical model of the tower crane, the parameters of which change with the dynamics of the crane and the shape and weight of the load. In this case, a single controller is used to control both the payload position and the swing angle. Only an approximate model of the tower crane is required for the simulation study.

The performance of the ANFIS controller has been compared with other controllers in terms of response time specifications including; delay time, rise time, settling time, steady-state error, and maximum overshoot. The time response of the system using PD, fuzzy-tuned PD, and fuzzy controllers for position is given in Figure 11(a), and for swing angle in Figure 11(b). When using an ANFIS-based controller, there was a clear improvement in the behavior of the system compared to the fuzzy controller, as given in Figure 12. Where Figure 12(a) shows the time response of the position, and Figure 12(b) for the swing angle. Referring to Table 3, the results show that the conventional PD controller achieved a stable response with a delay time of 1.298 seconds, a rise time of 4.148 seconds, a settling time of 10.567 seconds, and a maximum overshoot of 0.2%.

As it can be seen from the results that the use of conventional PD controller and fuzzy-tuned PD controller produces oscillation with amplitude of 20° and 18.25° respectively, compared to the fuzzy logic controller of about 6.06°. Although the position of the load follows the reference input, the oscillation of the sway angle requires treatment when using such model-dependent controllers that needs to update its parameters (K_p and K_d) with any change in tower crane dynamics. One of the reasons for using fuzzy logic to control a tower crane is its ability to control both the payload position and the swing angle without the need for an accurate mathematical model of the crane.

Table 3. Time response indicators for different controllers

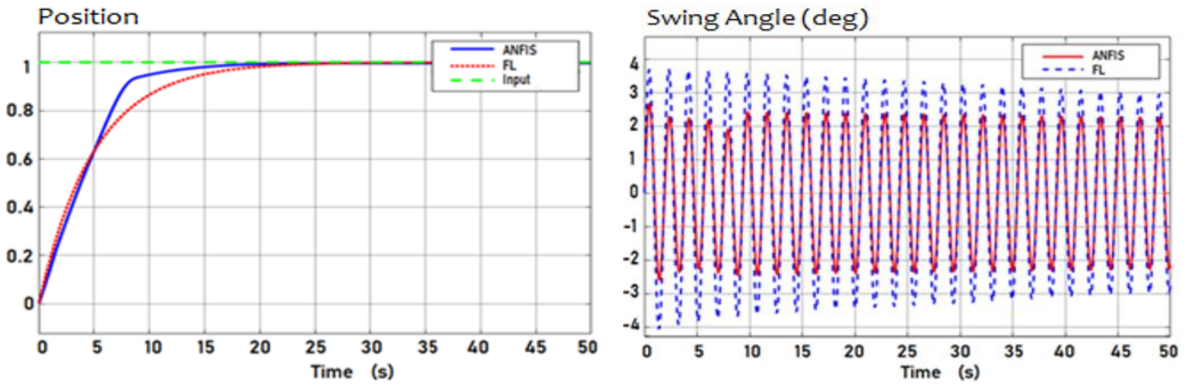
Position				
Controller type:	PD	Fuzzy tuned PD	Fuzzy logic	ANFIS
Delay time (s):	1.298	1.381	3.465	3.809
Rising time (s):	4.148	4.159	11.495	7.752
Settling time (s):	10.567	11.96	26.423	22.595
Overshoot %:	0.2%	0.6%	0	0
Steady state error:	0	0	0.001	0.003
Swing angle				
Controller type:	PD	PD tuned fuzzy	Fuzzy logic	ANFIS
Gamma (degree)	[-10.90 ~ 9.10]	[-9.85 ~ +8.40]	[-3.0 ~ +3.03]	[-2.28 ~ +2.28]



(a) (b)

Figure 11. Time response of the system using PD, fuzzy-tuned PD, and fuzzy controllers: (a) position and (b) swing angle

It can be seen from the previous results that the ANFIS-based controller is able to give a faster response compared to the fuzzy controller with rise time of 7.752 seconds, settling time of 22.595 seconds, minimum steady-state error and no overshoot. It is clear from the results that the swing angle fluctuation ranges from –2.28° to +2.28° for ANFIS controller, which is the lowest compared to other controllers. The main advantages of the proposed ANFIS controller are its ability to control both the payload position and swing angle as well as a model-independent approach that does not need to update its parameters depending on the dynamics of the tower crane. Figure 13 shows a comparison of the main indicators of the performance of the four controllers. These indicators show that the proposed ANFIS controller has the best performance and has better response compared to other controllers. Although the values of delay time, rise time and settling time are higher than the PD controller and the fuzzy-tuned PD controller, the swing angle fluctuations are less compared to other controllers, making it the best controller to control the position and swing angle of the crane.



(a) (b)

Figure 12. Time response of the system using ANFIS and fuzzy controllers: (a) position and (b) swing angle

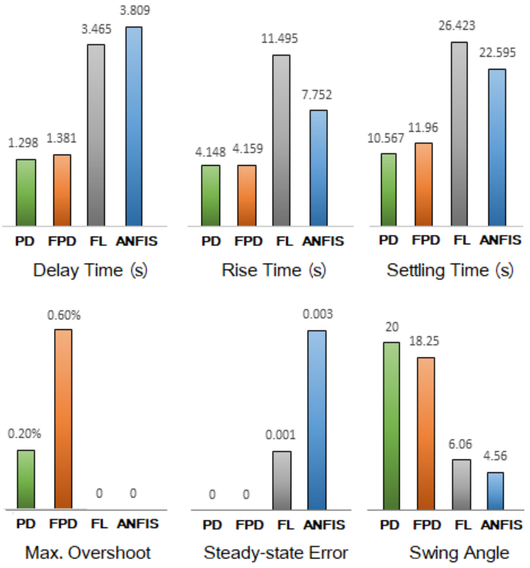


Figure 13. Performance comparison of four controllers

6. CONCLUSION

This paper introduced an intelligent controller for tower cranes to move the load from one point to another as quickly as possible so that the load fluctuation remains small during the transportation process and in the final position. The mathematical model of the tower crane is a set of nonlinear equations, and the design of the traditional control systems is mainly based on the mathematical model of the crane. Moreover, the mathematical model of the crane is simplified for control and analysis purposes. From the obtained results, it is proved that the ANFIS-based controller has a comprehensive advantage of robustness compared with the traditional PD controller, fuzzy-tuned PD controller and fuzzy controller. The ANFIS-based controller has better overall performance in terms of both payload position and swing angle variation. The oscillation angle of the payload is within ±2.28° with the ANFIS controller while it is about ±10° for the PD controller. In addition, the ANFIS controller is a model-independent approach and can be implemented by an embedded microcontroller. It is not necessary to update the parameters of the controller every time the dynamics of the crane or the shapes of the load change, because everything is done by the ANFIS approach. In this paper only one ANFIS controller is used for both payload position and swing angle control.

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BIOGRAPHIES OF AUTHORS

Saleh B. Al-Tuhaifi received his BSc degree in mechatronics engineering from the Hashemite University, Jordan in 2020. He is currently MSc student majoring in mechatronics engineering at Philadelphia University, Jordan, and working as mechatronics engineer in the department of operation and maintenance at the Arap Open Univesity, Jordan. His research interests include Embedded systems, Softcomputing, Robotics and automation. He can be contacted at email: sale7briemah@gmail.com, 202010547@philadelphia.edu.jo, sale7briemah@gmail.com, Research id: HKF-7985-2023.

Kasim Mousa Al-Aubidy received his B.Sc and M.Sc degrees in control and computer engineering from the University of Technology, Iraq in 1979 and 1982, respectively, and Ph.D degree in real-time computing from the University of Liverpool, England in 1990. He is currently a professor and dean of Faculty of Information Technology and dean of Architecture and Desisgn at Philadelphia University, Jordan. His research interests include embedded systems, robotics and automation, fuzzy logic, neural networks, genetic algorithm, and their real-time applications. He is also the chief editor of two international journals, and a member of editorial board of several scientific journals. He has coauthored 4 books, four chapters in books, and published 102 papers on topics related to computer applications. He can be contacted at email: kma@philadelphia.edu.jo.