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Intelligent Control of industrial gantry crane model "3D Crane"

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ABSTRACT

3D Crane represent Laboratory model of industrial gantry cranes which are widely used in industry. In this work, a dynamic model of 3D Crane is presented and tow artificial intelligence techniques were synthetized and applied to the model : Fuzzy Logic Control (FLC) and Adaptive Neural Fuzzy Inference System (ANFIS); the purpose of the control is the minimization of swing angles with continued reference trajectory in the three axes. A robustness test against external disturbance of the implemented controls was also apply. The results of the applied techniques are discussed.

Key words: 3D Crane, Dynamic model, Fuzzy Logic Control, Adaptive Neural Fuzzy Inference System, robustness, simulation.

1. INTRODUCTION

As known; Automatics is the science that deals with the modeling, analysis, identification and control of dynamic systems. Where one of its main objectives is to deal with industrial systems control problems like control of Gantry Crane System which are used for the fast and accurate transfer of heavy loads over long distances in many industrial environments.

As powerful transportation tools, overhead cranes have been widely used in many fields, including factories, warehouses, construction sites. In order to increase productivity, cranes are often controlled at high speed. However, the acceleration of the cart, necessary for movement, without Angle Control always induces unwanted oscillations of the suspended load. This reduces safety and increases the risk of falling and collision.

However, the problem of load tipping is an area where researchers have invested in order to move the payload along a trajectory with small oscillations, and good robustness [1].

The 3D Crane is a multivariable nonlinear electromechanical system, having a complex dynamic behavior, thus presenting difficulties in controlling it, because of the non-linearity and under-actuations present in the system. The laboratory crane "3D Crane" is a model of industrial crane, its behavior is similar.

For the important role of cranes in several sectors of industry, several crane control approaches are developed. References [2] and [3] have synthesized linear control laws use pole placement technique.in [4], authors proposed a state return command of a linear model with variable parameters with an observer. And for optimal control, we will find works as [5] which have established an optimization algorithm to mitigate the swing of load and ensure the trajectory continuation of the cart. Also [6] solved an issue of optimal control at minimum time by the principle of Pontriaguine; [7] suggested a linear quadratic LQ command with fixed gains and a change in mass of the load. Authors in [8] proposed nonlinear control based on a parametric estimation mechanism using self-adaptation methods. Other researchers have developed control strategies based on fuzzy logic. In order to eliminate oscillations of the load, [9] have proposed position control with a fuzzy logic corrector to control the position of the load and the length of the wire in parallel, Adaptive control has also been addressed in this framework. You can see here also: Fuzzy logic are widely used recently in control of crane and its model [10]-[14].Also Neuronal network and neuro-fuzzy gain place in the control techniques [15]-[20].

In the current study, we use the laboratory model "3D Crane" manufactured by Inteco Co. Ltd [21]. This model is intended for research work in the field of control, automation and construction technologies.

The dimensions of the 3D Crane (Figure1) are: 1 m in length and 1 m in height. The 1 kg mass payload is attached to the end of a wire and can be lifted by 1 m. The load can be raised or lowered depending on the length of the wire. The angles describe its position following the carriage. The rail and carriage describe a horizontal movement in the direction of the X-axis. The cart can describe a horizontal movement along the rail in the direction of the Y-axis. The system is also integrated with MATLAB / Simulink which allows the prototyping of control algorithm in real time. It can therefore be easily mounted and installed in a laboratory. The control signals generated in the MATLAB/Simulink computing environment are transmitted via the acquisition card and power amplifier to the motors, and the displacement of the elements of the slider is measured by using encoders from which the signal follows an analogous path returns to the application creating a closed exchange loop data.

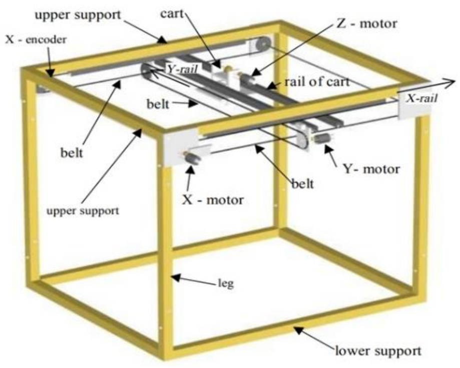


Figure 1: the 3D Crane model with actuators and sensors.

This paper is organized as follows: The mathematical model of the 3D Crane is presented initially. The intelligent controllers are then described and synthetized. Simulation Results of both two controls are provided, and a test of the robustness of the controllers against external disturbance was made. Finally, conclusions are drawn.

2. DYNAMIC MODEL OF THE 3D CRANE

In this section, we illustrate the mathematical model of the 3D Crane.

2.1 Propositions

The choice of coordinate system is important in modeling a physical system. Although the Cartesian system is easy to interpret, it is not practical to describe the dynamics of the rotational movement, so we choose the spherical system to model the 3D crane with five degrees of freedom.

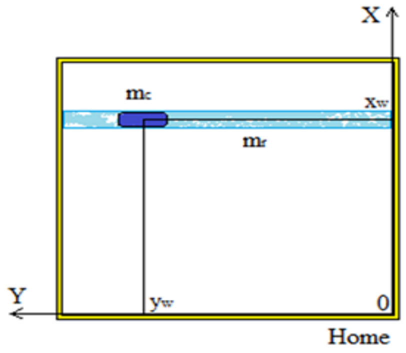


Figure 2: 3D Crane workspace.

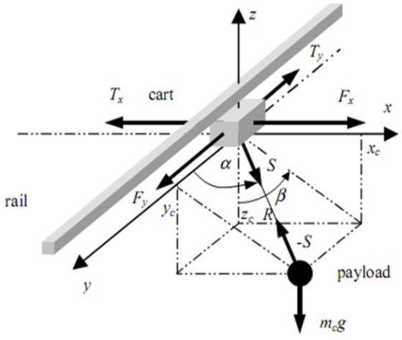


Figure 3: 3D Crane system (coordinates and control forces).

The position of the payload is described by the following equations:

$$\begin{cases} x_c = x_w + R\sin\alpha\sin\beta \\ y_c = y_w + R\cos\alpha \\ z_c = -R\sin\alpha\cos\beta \end{cases} \quad (1)$$

Table 1: Variables measured and forces applied to the system

Notation	Description
x_w	Distance between the system (trolley + rail) and the center of the construction [m].
y_w	Distance between the cart and the center of the rail [m].
R	The length of the cable [m].
α	The angle between the Y-axis and the cable [rad].
$(x_c; y_c; z_c)$	Coordinates of the payload.
S	Reaction force in the lift-line acting on the cart[N].
Fx	The force causing the rail to move rail with the cart [N].
Fy	The force acting on the cart along the rail [N].
FR	The force controlling the length of the lifting cable [N];
Tx, Ty, TR	Friction forces [N].

2.2 Dynamic Model

The Using the Newton's laws in the reference about the 3D crane subjected to forces $\sum F_{ext}$, we get:

$$\begin{cases} m_c\ddot{x}_c = -s_x \\ m_c\ddot{y}_c = -s_y \\ m_c\ddot{z}_c = -s_z - m_c g \end{cases} \quad (2)$$

$$\begin{cases} (m_w + m_s)\ddot{x}_w = F_x - T_x + s_x \\ m_w\ddot{y}_w = F_y - T_y + s_y \end{cases} \quad (3)$$

where:

$$\begin{cases} S_x = S\sin\alpha\,\sin\beta \\ S_y = S\cos\alpha \\ S_z = -S\sin\alpha\,\cos\beta \end{cases} \quad (4)$$

The following state variables are considered:

$$\begin{aligned} x_1 = y_w, x_2 = \dot{x}_1 = \dot{y}_w \\ x_3 = x_w, x_4 = \dot{x}_3 = \dot{x}_w \\ x_5 = \alpha, x_6 = \dot{x}_5 = \dot{\alpha} \\ x_7 = \beta, x_8 = \dot{x}_7 = \dot{\beta} \\ x_9 = R, x_{10} = \dot{x}_9 = \dot{R} \end{aligned} \quad (5)$$

The following nonlinear state-space of the system is obtained:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = N_1 + \mu_1 c_5 N_3 \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = N_2 + \mu_2 s_5 s_7 N_3 \\ \dot{x}_5 = x_6 \\ \dot{x}_6 = \dfrac{(s_5 N_1 - c_5 s_7 N_2 + (\mu_1 - \mu_2 s_7^2) c_5 s_5 N_3 + V_5)}{x_9} \\ \dot{x}_7 = x_8 \\ \dot{x}_8 = \dfrac{-(c_7 N_2 + c_5 s_7 N_2 + \mu_2 s_5 c_7 s_7 N_3 + V_6)}{s_5 x_9} \\ \dot{x}_9 = x_{10} \\ \dot{x}_{10} = -c_5 N_1 - s_5 s_7 N_2 - (1 + \mu_1 c_5^2 + \mu_2 s_7^2 s_5^2) N_3 + V_7 \end{cases} \tag{6}$$

With:

$$\begin{gathered} s_n \equiv \sin x_n, \quad c_n \equiv \cos x_n, \\ V_5 = c_5 s_5 x_8^2 x_9 - 2x_{10} x_6 + g c_5 c_7 \\ V_6 = 2x_8 (c_5 x_6 x_9 + s_5 x_{10}) + g s_7 \\ V_7 = s_5^2 x_8^2 x_9 + g s_5 c_7 + x_6^2 x_9 \end{gathered} \tag{7}$$

3. FUZZY LOGIC CONTROLLER

In this section we will synthesize the fuzzy logic control and applied it to 3D crane via MATLAB Simulink. Fuzzy Logic has been invented in 1965 by Lotfi A. Zadeh professor at the University of California in Berkeley [22]. This technique has also been used in control systems. Fuzzy control is now the standard control method which is a constituent of many industrial systems and companies advertise it no more. The used technique is mostly based on application of fuzzy IF-THEN rules. The figure 4 show the basic structure of fuzzy logic control.

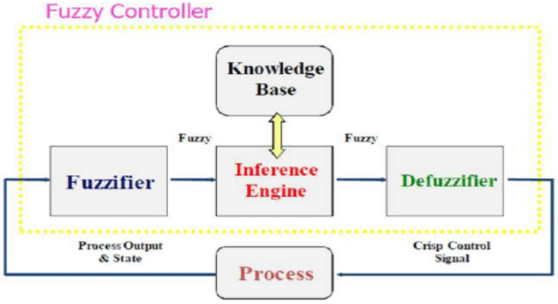


Figure 4: Basic structure of a fuzzy controller.

3.1 Control design

Most fuzzy controllers have been designed based on human operator experience and/or control engineer knowledge.

In this case we have to design a fuzzy logic control via MATLAB® Fuzzy logic Toolbox after we determine the crisp inputs. For simplicity we will separate the control on 3 FLC following the 3 motors control in each axis x, y (Figure 5) and z (Figure6). For the axis x and y we consider angles alpha and beta as inputs of FLC of axis x and y controller respectively.

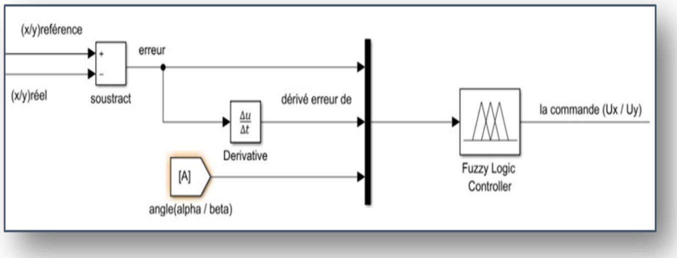


Figure 5: Fuzzy regulator of X and Y axis.

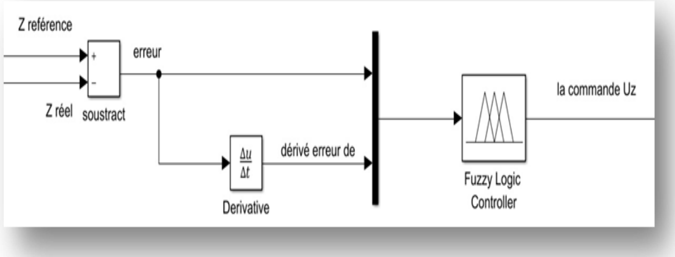


Figure 6: Fuzzy regulator of Z axis.

We represent the fuzzy sets of input where its number is 3 and fuzzy sets of input where its number is 5 as following:

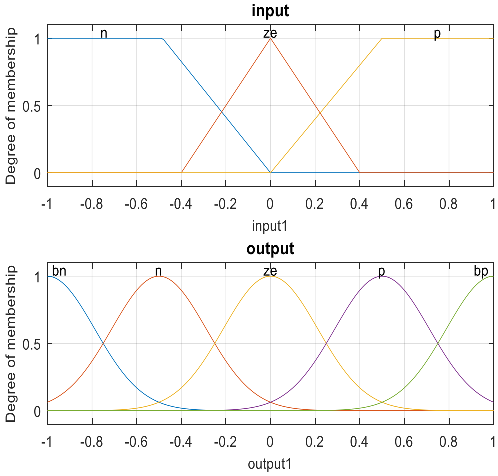


Figure 7: Membership Functions of the Fuzzy Regulator.

Membership function for the fuzzy logic controller inputs is (Figure 7): BN – big negative, N – negative, Z – zero, P – positive, BP – big positive.

The logic of the rules in the fuzzy regulator of the X and Y axis is to apply the force in an opposite direction of the swing angle, we obtain 27 rules (If-Then) and this is examples for language rules:

- If error is N and change-in-error N and angle P Then force is BN.
- If error is Z and change-in-error Z and angle P Then force is P.
- If error is N and change-in-error Z and angle P Then force is Z.

And for axis Z we obtain 9 rules (If-Then) and this is examples for language rules:

- If error is N and change-in-error N and Then force is BN
- If error is N and change-in-error Z and Then force is N.
- If error is N and change-in-error P and Then force is Z.

4. ADAPTIVE NEURAL FUZZY INFERENCE SYSTEM ANFIS

ANFIS is a kind of artificial neural network that is based on Takagi–Sugeno fuzzy inference, it was developed by Jang in 1993[23].A combined neur-ofuzzy approach has seen enormous preferences recently from researchers working in different domains [24].

ANFIS structure can be described as a multi-layered neural network as shown in (Figure. 8). the first layer is for a fuzzification is called the input layer, the second layer multiplies incoming signals, the third layer normalizes the membership functions (MFs), the fourth layer execute the consequent part of the fuzzy rules, and finally the last layer computes the output of fuzzy system by summing up the outputs of layer fourth[25].

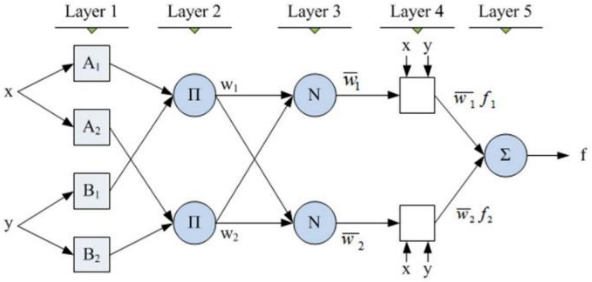


Figure 8: Basic ANFIS structure.

The technique uses the Hybrid learning procedure based on back-propagation for the parameters optimization of the premise parts and the "least squares" method for parameter resolution. This model is implemented in the “Neuro-Fuzzy” toolbox of MATLAB/Simulink and gives good results for the approximation of nonlinear functions.

In our case; for the learning data we used the data-inputs / outputs of the PID controllers applied to the same system. Angles are considered ANFIS entry. The learning is achieved in the table as follows:

Table 2: Learning parameters

	AXIS X	AXIS Y	AXIS Z
Number of rules	3*3*3=27	3*3*3=27	3*3=27
Function Type	Gaussian	Gaussian	Gaussian
Output function	linear	linear	linear
Learning method	hybrid	hybrid	hybrid
Number of epochs	60	60	60

5. SIMULATION RESULTS AND DISCUSSION

5.1 Fuzzy Logic Control

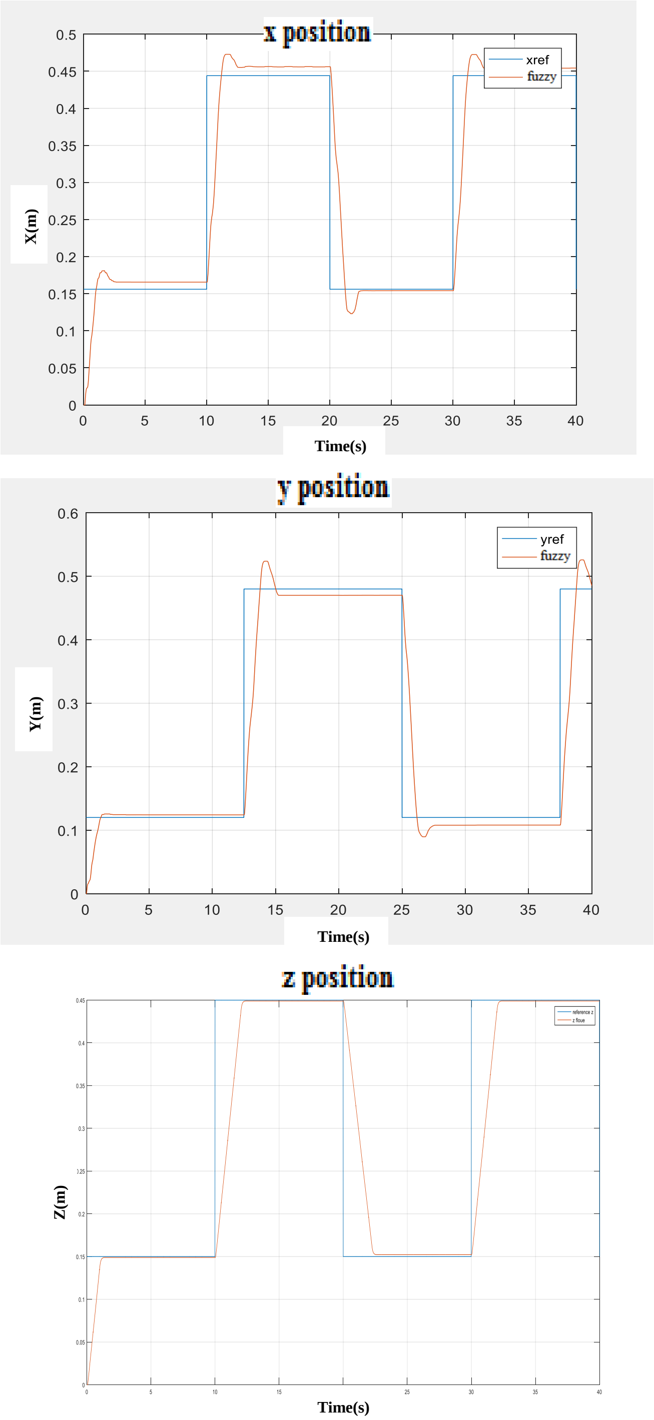


Figure 9: Tracking results of the desired positions along the axes (X, Y, Z).

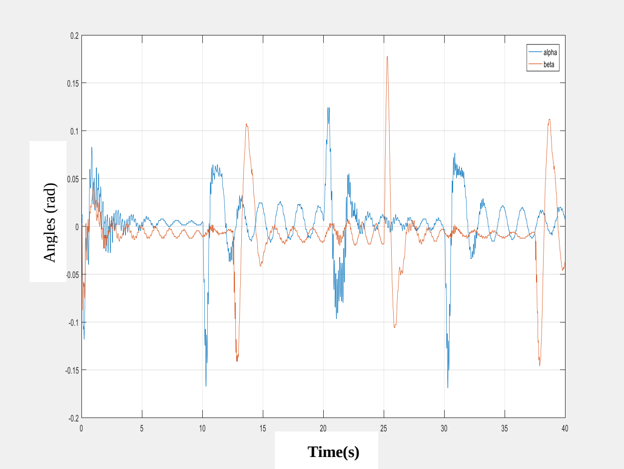
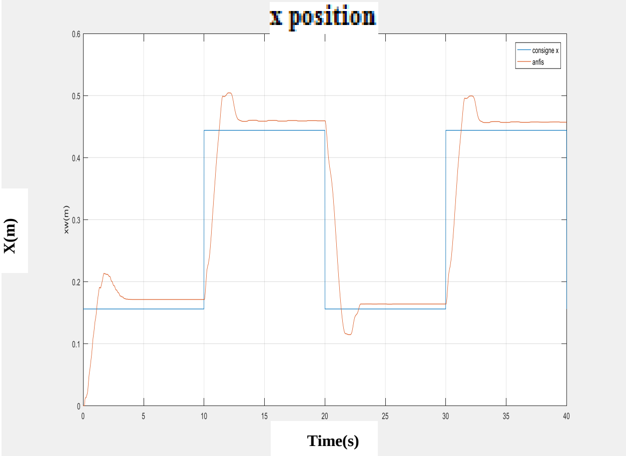
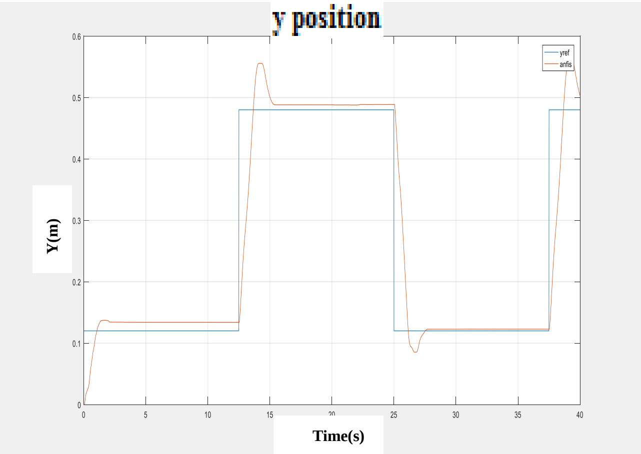


Figure 10: the angles α and β.

5.2 ANFIS control





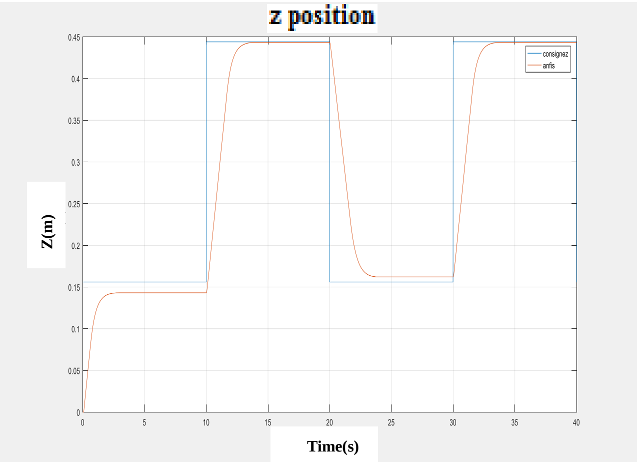


Figure 11: Tracking results of the desired positions along the axes (X, Y, Z).

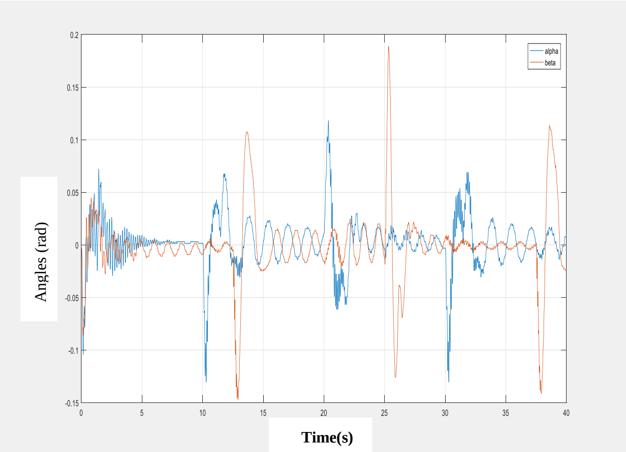


Figure 12: the angles α and β.

From the simulation results above for both controllers we can see clearly that the Fuzzy controller (Figure.9; Figure.10) reaches the reference trajectory in a finite time duration and presents an acceptable minimization of the oscillations (low oscillations of the angles α and β) with an overshoot of 4% and 8 % in the x and y axes. We can also conclude from the (Figure.11; Figure.12) that the ANFIS regulator gives a fast response with a good minimization of oscillations (angles α and β). This allowed us to say that ANFIS gives a powerful result especially at the level of the z axis and an acceptable result at the level of the X and Y axes. Nevertheless, we have an overshoot (10 and 12%). And this is due to the lack of optimal learning and structural complexity at the x and y axes.

6. TEST OF ROBUSTNESS

In order to test the robustness of the two controllers implemented against the external disturbance, we applied a disturbance to the system, the latter was a random force at times t=5 sec and t=20sec.

6.1 Fuzzy control

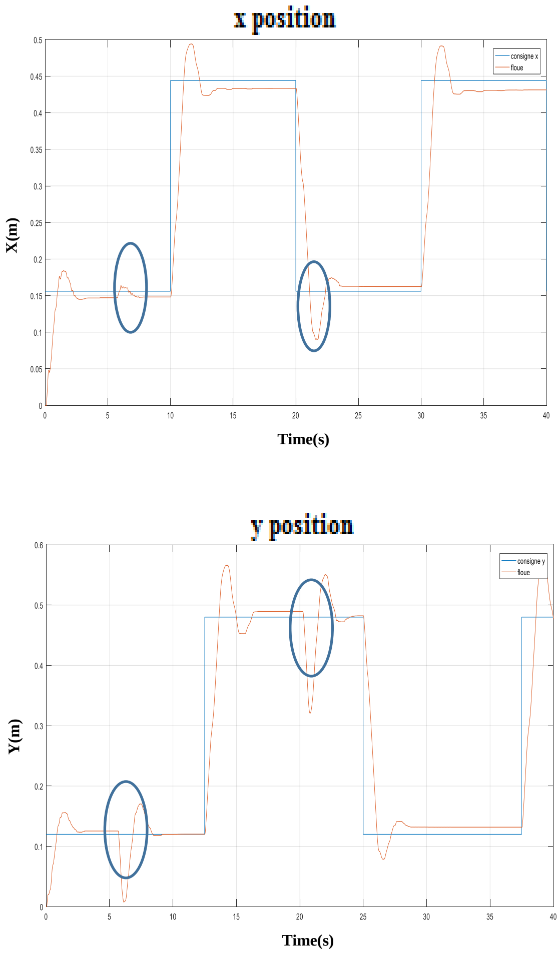


Figure 13: Tracking results of the desired positions along the axes (X, Y) with disturbance.

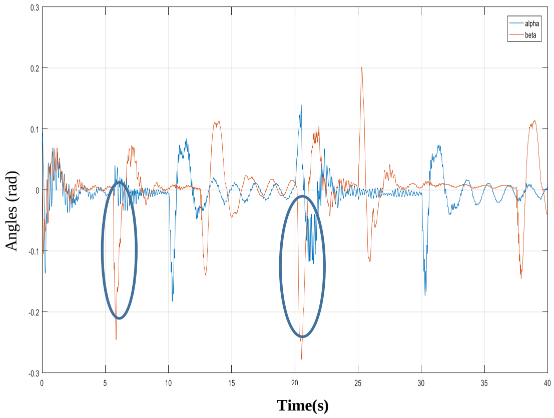


Figure 14: the angles α and β with disturbance.

6.2 ANFIS control

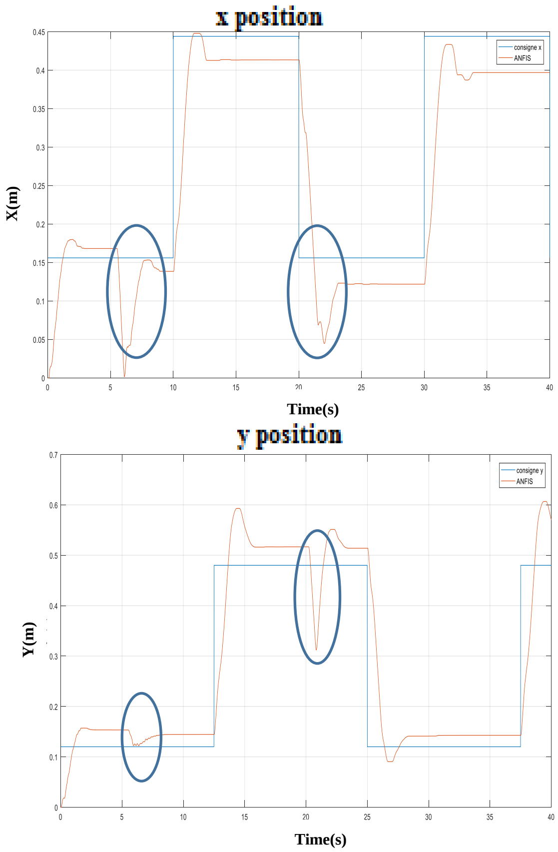


Figure 15: Tracking results of the desired positions along the axes (X, Y) with disturbance.

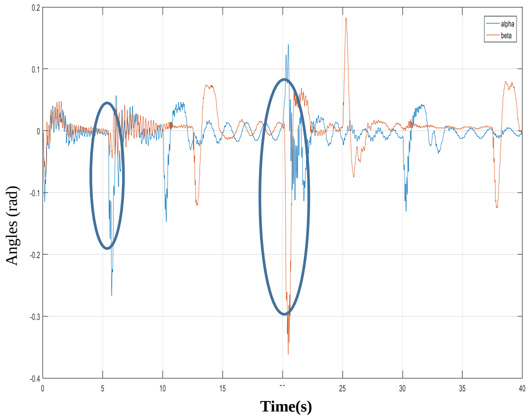


Figure 16: the angles α and β with disturbance.

From the simulation results of robustness tests for both controllers: Fuzzy Logic and ANFIS, we can see clearly that than when an external disturbance is applied (manual mass swinging) the fuzzy control (Figure.13; Figure.14) gives results eliminate the disturbance in a short time and the oscillation of the angles is compensated and the mass stabilizes and system can return to the desired position at the axes with effective disturbance rejection .On the other hand, control by ANFIS (Figure.15; Figure.16) does not give good tracking of the desired trajectory and takes a long time to eliminate disturbances. This leads us to conclude that robustness against external disturbances is not guaranteed by the ANFIS command.

7. CONCLUSION

In this paper, we presented the dynamic model of "3d Crane" which represent prototype model of real overhead gantry cranes and his controlling with artificial intelligence technics as fuzzy logic and ANFIS controllers; the purpose of the controlling is the minimization of swing angles with continued reference trajectory in the three axes. The high order of our system and its complex nature, caused a difficulty in the choice of optimal structure of fuzzy regulator and that demonstrates its major disadvantages lack of precise directive for the design of a rule;

Both controllers gives a great advantage of not needing a modeling of our system which is very complex (as shown in section 2) to process.

The use of a neuro-fuzzy control (ANFIS) gives good results in the context of learning condition and the database used; therefore, the need for a training database of an existing control which is not always available represents its disadvantage major (in our case we used a PID controller in the learning); thus, the irrelevant database and the optimal way chosen in the learning makes the control by ANFIS not always an effective choice.

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