Enhancing the Feedforward –Feedback Controller for Nonlinear Overhead Crane Using Fuzzy logic controller

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Abstract. Due to the demand for transportation of masses and products in power stations, factories, and offshores, the overhead cranes are commonly used to do these tasks. It has necessary that, it should be safely, quickly and accurately as possible as without collision or highly swinging, or in other words saving time and reduce costs. If an operator runs manually the crane more time required, in addition many larger companies create automatized crane like a milling machine. Although, there are many researchers have suggested many controllers, this subject is still a challenge for the designer. The suddenly change of loads or the air streams or even the flexibility change of cable of cranes working in foundries may cause disturbance and variation in the control parameters. However, in this paper a new feedforward and feedback controller has designed to move the crane as fast as possible with small angle of oscillation firstly, then a Fuzzy logic controller has added to gather to the controller for enhancing the efficiency of the system. Finally, the MATLAB-Simulink models have been implemented for analysis and simulation of the suggested controller. The achieved results demonstrated the effectiveness of the proposed method. Moreover, the proposed methods have robustness to cope with parameters variations.

1. Introduction

Compared to other models of the cranes, the overhead cranes have some advantages such as low cost, easier assembly and less maintenance [1].

Due to the demand for transportation of masses and products in power stations, factories, and offshores the overhead cranes are commonly used to do these tasks. Transferring the patients or disables to bed, bath or toilet have never been easier. However, using a new design of overhead crane system can make the lift and transfer of them easy [2].

Recently since the cranes becoming larger, and heavy payloads are handled, the manual controlling has become difficult [3]. Generally, the expertise of the operator is depend upon for safe payload transporting and accurate positioning [4]. Acceleration or deceleration of overhead cranes usually produces swinging of the pensile payload [5] [6]. This swinging increases the likelihood of accidents and reduces operational efficiency, furthermore, when the cranes are run manually, more time will be required [7].

Therefore, transporting the loads to a desired location precisely without impact with other equipment, should be the goal of controlling the overhead cranes [8]. Subsequently, it is necessary to control the crane quickly such that the wing angle of load, the position error of cart, in spite of exciting the system by disturbance [9].

Toward providing accurate and robust control schemes much works have been done for overhead cranes, and minimizing dependence on the system operator by involving automation control.
In recent tendencies even the different advance control propositions have been developed and have been tested for many dynamical systems control, it is recommended that the naivety of control algorithms in addition to the verification of control aim [10].

The execution of the crane dynamical systems being controlled is wanted to be optimal. There are many control techniques have been offered for this purpose, including the PID controller, linear quadratic, genetic algorithm GA, artificial neural network ANN, Fuzzy Logic control FLC, etc.

A classical PID feedback controller for anti-swing is presented by Solihin et al. [11]. However, feedback control (PID) is less sensitive for modeling error. Önen and Cakan [8] and Santhi and Beebi [12] introduced LQR method which is not complicated and effective. However, when the system is excited by external affect, it might veer from the equilibrium limits. Hence, ensuring the stability of the controller is not easy with it. Based on GA, Xiao et al. [13] presented a control algorithm for improving the control performance of the crane system. However, it is theoretically complicated for the GA algorithm to guarantee the stability precisely at the equilibrium point. Moreover, the designing of the control is relatively complicated. Hence, it is unsuitable for practical applications. Abe [14] used neural networks NN for control overhead cranes. However, one of the limitations of the neural network control method, it demands a collection of considerable information from experiments for networks training and checking.

More interest has given for using the approach of Forward-Feedback (FF) combination in the engineering control application for suppressing vibrations. Cazzulani et al. [15] implemented FF method. A control logic for suppressing vibrations producing from both large boom motion and pumping of concrete was implemented. This control algorithm was demonstrated using numerical simulations and experimental campaign. Wu et al. [16] a FF controller is presented to control inverted pendulum. They implement the feedforward part of the controller for suppressing the disturbance (displacement of the cart). Nagaoka and Sato [17] presented FF controller for controlling a CNC machine tool. A suppression in the vibration, an error reducing in path tracking, and a highly symmetric path are achieved by using this controller. Wu at el. [18] introduced a hybrid control method combining Feedforward and Feedback controllers for chatter suppression of robot machine. However, this study focused on control of the suppression of disturbance but did not solve the problem of a tracking error increasing due to the delay of feedforward controller.

A feedforward controller and feedback (PID) controller at the same time is presented in [19]. However, this approach yields a set of differential algebraic equations (DAE) with higher index which have to be solved numerically to overcome this difficulty.

For many years, fuzzy logic controllers (FLC) are widely used in control applications. Mainly, FLC is the most appropriate and efficient in both multi-input, single-output (MISO) and multi-input, multi-output (MIMO) systems [4]. Its successes in process control have been approved in many applications such as missiles, jet engine, automatic transmission, stability controlling of vehicle, image processing, position and process control and many others.

Recently, researchers have focused their attention into the control of the overhead crane system and its parameter variations using fuzzy logic technique. For enhancing the robustness and overcome parameters variations of an overhead crane system, Solihin et al. [11] designed a fuzzy tuned-PID controller for tuning the gains. Hai et al. [20] presented an intelligent algorithm for 2-D overhead crane system which based on PID and Fuzzy sliding mode control. Experimental verification has done using 3-D overhead crane. However, in addition to the complicated mathematical assumption that used, the simulation results show that any simple change of the mass of the trolley leads to high vibration in the swing angle and it takes a long time for damping. Petrenko and Alavi [21] implemented Fuzzy logic FLC and genetic algorithm GA to control overhead crane. Shi et al. [22] and Popadic et al. [23] designed a fuzzy crane controller which depends on a Linear Quadratic (LQ) crane controller.

Arapci [3] and Kharola [24] used ANFIS offline controller where [24] implemented an ANFIS controller for training the data sets obtained from simulation of PID controller of overhead crane system. In Li et al. [25], self-adaptive fuzzy PID controller is presented to tune PID parameters combined with only an angle feedforward controller for linearized bridge crane.
Unfortunately, besides the nonlinear disturbance such as wind, hit, and friction of track, the overhead crane is highly nonlinear dynamic system. However, it is difficult to efficiently control such system by only basic fuzzy controller [5] where the desired performance is unacceptable. This motive to present, in this paper, a control methods which have implemented at first; a feedforward-feedback scheme for driving the 2-D overhead crane system to a desired position with reduced swing under the effect of disturbance input forces. The second scheme combines fuzzy strategy with first scheme to enhance the performance and the robustness against disturbance input forces and to expedite the pace of attenuation of the swing angle.

This study is structured in five sections. General introduction and literature review about controlling of overhead crane system is introduces in Section 1. Section 2 describes an overhead crane dynamic model. In Section 3, a feedforward-feedback controller and a combination of feedforward-feedback and fuzzy method for driving the crane are discussed. MATLAB-Simulink models, and simulation results under different disturbance input forces are analyzed in Section 4. In section 5, conclusions are given.

2. Mathematical modelling of overhead crane

The free body diagram of an overhead crane with payload is shown in Figure 1. It assumed that the rope mass is ignored, no friction exist in the hinge, and the payload is regarded as a material particle. The trolley mass is \(M\), the payload mass \(m\), the rope length \(l\), the swing angle of the payload with respect to vertical line \(\theta(t)\) upward direction, the trolley position with respect to the origin \(x(t)\), and the externally x-direction force on the cart \(u(t)\), and gravity force acts on the payload mass \(g\).

Assuming the wind effects (or may be friction between the trolley and the track) as an additional disturbance on the system, and let \(F_d\) represent this disturbance force on payload.

Using Euler-Lagrange method [26], the Lagrangian equation with respect to the generalized coordinate \(q_i\) with external disturbance input force could be written as:

\[
\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = T_i
\]  

\(\text{(1)}\)
Where $i=1, 2$, $L = K - P$ (K means the system kinetic energy and P denotes the system potential energy), $q_i$ is the generalized coordination (where $q_1$ and $q_2$ indicate $x$ and $\theta$, respectively), and $T_i$ is the external force.

The system kinetic energy can be depicted as

$$K = \frac{1}{2} M x^2 + \frac{1}{2} m v^2$$

(2)

Here, $v$ is a vector and it denotes the payload velocity, defined as

$$v^2 = v_x^2 + v_y^2$$

(3)

where $v_x = \dot{x} + l \dot{\theta} \cos \theta$, and $v_y = -l \dot{\theta} \sin \theta$. The system potential energy owing to pendulum movement, written as

$$P = mgl(1 - \cos \theta)$$

(4)

Hence,

$$L = K - P = \frac{1}{2} M x^2 + \frac{1}{2} m v^2 - mgl(1 - \cos \theta)$$

(5)

$$= \frac{1}{2} M \ddot{x}^2 + \frac{1}{2} (\dot{x}^2 + \dot{l}^2 \dot{\theta}^2 + 2\dot{x} \dot{l} \dot{\theta} \cos \theta) - mgl(1 - \cos \theta)$$

(6)

Substituting the value of $L$ from equation (5) into Euler-Lagrange equations below,

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{x}} \right) - \frac{\partial L}{\partial x} = u + F_d$$

(7)

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

(8)

yields

$$(M + m) \ddot{x} + ml \ddot{\theta} \cos \theta - ml \dot{\theta}^2 \sin \theta = u + F_d$$

(9)

$$l \ddot{\theta} + \dot{x} \cos \theta + g \sin \theta = 0$$

(10)

3. Controllers design

3.1. PID controller

To derive the overhead crane along a desired position, while ensuring that the pendulum is stabilized vertically downward at the end of the motion, a conventional PID controller is implemented [10]. This PID controller is composed of two PID controllers one for controlling the displacement loop of the crane $u$, and the second PID for controlling the loop of angle $u_\theta$, according to the equations:

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt}$$

(11)
\[ u_x = K_{px} e_x(t) + K_{ix} \int e_x(t) dt + K_{dx} \frac{de_x(t)}{dt} \]  

(12)

where \( e_\theta(t) \) is the error of angle and \( e_x(t) \) is the error of the displacement. \( K_p, K_i, K_d \) are the gains of the controller which have been found by using trial and error then watching the behaviour of the system. Because of the dynamic coupling of pendulum angle and cart position, any change in one PID control parameters will lead to change in the behaviour of all control system.

### 3.2. Feedforward – Feedback controller

To obtain obvious improvements in the performance of crane system, a combination of feedforward and feedback (conventional PID) controller is designed, due to the ability of feedforward controller to preclude disturbance on the system [18] [27]. After manipulation of the input disturbance force by an inverse dynamics model, it is fed forward to the output of feedback (PID) controller, as shown in Figure 2. Here the feedback controller is used to control the swing angle and displacement of cart, whilst the feedforward controller is used to neutralize the disturbance input force. For feedforward plus feedback control shown in Figure 2, the closed loop relationship can be found as [27]:

\[ y(s) = \frac{G_d(s) - G_d(s) G_{ff}(s)}{1 + G_p(s) G_{fb}(s)} F_d(s) + \frac{G_p(s) G_{fb}(s)}{1 + G_p(s) G_{fb}(s)} r(s) \]  

(13)

 Applying the disturbance force to the crane system will generate a corresponding force, which is caused from the internal inverse dynamics of the crane system, therefore the actual displacement, and angle will be deviated from the desired. Nevertheless, the feedforward controller output force equalizes this corresponding force. As a result the effect of the disturbance input force will be eliminated.

![Figure 2. Feedforward-Feedback control block diagram for overhead crane system](image)

### 3.3. Feedforward – Feedback and Fuzzy controller

Since it was presented by Mamdani in 1974, FLC has been introduced and has been applied in a different ways. A block diagram showing the basic configuration of a fuzzy logic controller is shown in Figure 3. Fuzzy Logic Controller, with general structure, consists of four basic conceptual components as fuzzification, knowledge base, inference and defuzzification. Fuzzification block converts a crisp inputs of a process variable into a fuzzy set. Fuzzy set theory provides a systematic calculus to deal with uncertain information linguistically, and it carries out numerical computation by using linguistic labels specified by membership function. The fuzzy logic controller's knowledge base comprises a data base and rule base [28] [29]. The data base gives necessary definitions for linguistic control rules and fuzzy data manipulation. Every rule base is composed of IF-PART of the rule called
condition part, and THEN-PART of the rule called conclusion part, hence, the rule base is a collection of such rules. The inference mechanism implements the fuzzy rules in the rule base to produce fuzzy conclusion. Finally, the defuzzification process into crisp outputs [30] converts these fuzzy conclusions. Among many inference methods to design of fuzzy logic controller, there are two famous approaches; Mamdani method which has been used in this study, and Sugeno method.

4. Simulation, Results and Discussion

A nonlinear dynamic model of overhead crane system is modeled using MATLAB-Simulink with forward-feedback controller and forward-feedback-fuzzy controller. The parameters of crane system, in this study, are selected as: \( M = 0.25 \text{ Kg}; m = 1.00 \text{ Kg}; L = 0.6 \text{ m}; \) reference horizontal position of the cart (\( x \)) = 0.2 m.

For simulating the disturbance input forces a band limited white noise is used with two cases of frequencies. The values selected are: (1) Low frequency disturbance: noise power = 0.01, (2) High frequency disturbance: noise power = 0.03, while the sample time= 0.01, and seed= 23341 for both cases.

In this study, two control strategies have been used for obtaining the optimal performance of nonlinear crane system are: (i) forward-feedback controller FFC (ii) forward-feedback-fuzzy FFF controller. Each controller has been studied with low frequency then with high frequency disturbance input, respectively. The control parameters seen in table 1 have been found using trial and error, then checking the behavior of controller to be the most favorable.

The Simulink models for controlling of nonlinear crane by forward-feedback controller FFC PID strategy for both cases of low frequency and high frequency disturbance input can be seen in Figure 4. As mention before, for modelling the disturbance input force effect, the band-limited white noise is added to the crane. The pendulum swing angle \( \theta \) and cart displacement \( x \) taken into account for the measurement. The desired swing angle and reference displacement are set to \( 0^\circ \) and 0.2 m, respectively.
Table 1. PID controller parameters.

| Control Scheme                     | Cart PID Controller | Pendulum PID Controller |
|------------------------------------|---------------------|-------------------------|
|                                    | $K_p$   | $K_i$   | $K_d$   | $K_p$ | $K_i$ | $K_d$ |
| Feedforward- Feedback (PID)        | 90      | 1       | 40      | 100   | 0     | 0     |
| Feedforward- Feedback (PID)- Fuzzy| 70      | 1       | 50      | 120   | 0     | 10    |

The Simulink model of forward-feedback-fuzzy FFF controller (PID-Fuzzy) for controlling the nonlinear crane system with low frequency disturbance input using Mamdani method FIS is shown in Figures 3 and 5. The angle $\theta$ and angular velocity $\dot{\theta}$ are taken as inputs to fuzzy controller of angle, while cart displacement error $e_x$ and cart velocity $\dot{x}$ are inputs to fuzzy controller of cart, respectively, as can be seen in Figure 3.

The universe of discourse for nonlinear crane system, in each fuzzy controller using Mamdani method FIS, are: $x = [-0.2, 0.2]$, $\dot{x} = [-1, 1]$, $u_x = [-0.1, 0.1]$ for fuzzy controller of cart displacement, and $\theta = [-0.1, 0.1]$, $\dot{\theta} = [-1, 1]$, $u_\theta = [-0.1, 0.1]$ for fuzzy controller of angle. Both angle and displacement fuzzy controller have utilized seven triangular memberships (NL, NM, NS, Z, PS, PM, PL) to describe each variable [10] and [7]. For each controller 49 rules are used as tabulated in tables 2 and 3.

Table 2. Rules for the pendulum angle fuzzy controller

| Control Force $u$ | Pendulum angular velocity $\dot{\theta}$ |
|-------------------|-----------------------------------------|
|                   | NL                                      | NM                                      | NS                                      | Z                                      | PS                                      | PM                                      | PL                                      |
| Error in swing    | NL                                      | NL                                      | NL                                      | NL                                      | NL                                      | NM                                      | NS                                      | Z                                      |
| Angle $\theta$    | NL                                      | NL                                      | NL                                      | NM                                      | NS                                      | Z                                       | PS                                      | PM                                      |
| $\dot{\theta}$    | PS                                      | NM                                      | NS                                      | Z                                       | PS                                      | PM                                      | PL                                      | PL                                      |
| $\dot{\theta}$    | PS                                      | NS                                      | Z                                       | PS                                      | PM                                      | PL                                      | PL                                      | PL                                      |
| $\dot{\theta}$    | PL                                      | Z                                       | PS                                      | PM                                      | PL                                      | PL                                      | PL                                      | PL                                      |

Table 3. Rules for the cart displacement fuzzy controller

| Control Force $u$ | Cart velocity $\dot{x}$ |
|-------------------|-------------------------|
|                   | NL                      | NM                      | NS                      | Z                      | PS                      | PM                      | PL                      |
| Error in cart position $e_x$ | NL | NL | NL | NL | NL | NM | NS | Z | PS | PM | PL |
| $e_x$             | NL                      | NL                      | NL                      | NL | NM | NS | Z | PS | PM | PL | PL |
| $e_x$             | NM                      | NL                      | NL                      | NL | NM | NS | Z | PS | PM | PL | PL |
| $e_x$             | NS                      | NL                      | NL                      | NL | NM | NS | Z | PS | PM | PL | PL |
| $e_x$             | Z                       | NL                      | NL                      | NL | NM | NS | Z | PS | PM | PL | PL |
| $e_x$             | PS                      | NM                      | NS                      | Z | PS | PM | PL | PL | PL | PL | PL |
| $e_x$             | PM                      | NS                      | Z | PS | PM | PL | PL | PL | PL | PL | PL |
| $e_x$             | PL                      | Z | PS | PM | PL | PL | PL | PL | PL | PL | PL |

With respect to the case of with low-frequency disturbance input, it observed that the payload (pendulum) swing was effectively damped vertically downward position smoothly, in approximately 6 seconds, after two major overshoots and two minor undershoots as seen in Figures 6a and 6b, whilst quickly with minor oscillations for the case of with high-frequency disturbance. The cart displacement $x$ arrives the reference distance of 0.2 m, in approximately 6 seconds, after two minor overshoots and a minor undershoot.

Simultaneously, PID-Fuzzy controller scheme show the same behavior of pendulum but less amplitude of oscillation than using only PID controller, and it stabilizes in approximately 5 seconds which it is important in real applications.

In the same context, the cart displacement $x$ arrives the reference displacement of 0.2 m in approximately 5 seconds after two minor overshoots and a minor undershoot.
Feedforward controller, by analysis and tests of the model, clearly can react before the effect of the disturbance appears in the plant (crane dynamic system) output.

For ensuring the activity of the suggested controllers for the transfer of the overhead crane safely, some factors that can possibly influence the control should be studied. Essentially, it is important to examine the control performance when the crane is subjected to an external high frequency disturbance. Here, in the Simulink modelling, the Noise power of the Band-Limited White Noise is increased from 0.01 to 0.03 for both of feedforward-feedback and feedforward-feedback and fuzzy controllers, respectively. By observing the responses in Figures 7a and 7b, the noise effect is clear although the controller drives the crane to the desired position with approximately the same maximum angle. Thus the controller can suppress the high frequency disturbance, and feedforward-feedback and fuzzy controller is the better.

When the mass of the payload is changed, the controller can still transfer the cart to the specified distance with the similar displacement response behavior, Figures 8a and 8b, and with identical maximum angle nearly. The maximum difference has not exceeded 0.08 ° for feedforward-feedback and 0.14° for feedforward-feedback and fuzzy. Thus the settling time and the maximum swing angle cannot be affected by the change of the mass of payload, and the validity of the proposed method is demonstrated to some extent.
Figure 6. The responses by Feedforward-Feedback control and Feedforward-Feedback+Fuzzy control with Simulink model with low frequency disturbance

Figure 7. The responses by Feedforward-Feedback control and Feedforward-Feedback+Fuzzy control with Simulink model with high frequency disturbance

Figure 8. Comparison between the responses by Feedforward-Feedback control and Feedforward-Feedback+Fuzzy control with Simulink model for increasing the pendulum mass m
To further verify the proposed methods, different cable lengths were tested. Certainly, longer cable leads to larger swing oscillations, Figures 9a and 9b. However, the controller has the ability to transfer the crane to the desired location efficiently and with safe swinging.

In addition, to prove the controller performance when the desired displacement is increased, Figures 10a and 10b show that the controller can transfer the crane even for a far distance (0.3m) effectively. However, the maximum swing angle has increased but within acceptable limits.

\[ \text{Figure 9. Comparison between the responses by Feedforward-Feedback control and Feedforward-Feedback+Fuzzy control with Simulink model for increasing the pendulum length } L \]

\[ \text{Figure 10. Testing the responses by Feedforward-Feedback control and Feedforward-Feedback+Fuzzy control with Simulink model with low disturbance frequency for increasing the desired displacement } x. \]

As can be seen in the tables 4, 5, 6, and 7 and comparing the results between the two control schemes, one can conclude that the method of (FF+F) has enhanced the performance of the crane system. Where the settling time for swinging has decreased, in addition the maximum angle of oscillation has been decreased also, and finally the trolley can reach the desired position in a minimum oscillation comparatively with the FF controller only. Clearly, both the proposed method of feedforward-feedback and feedforward-feedback and fuzzy controllers can effectively control the overhead crane.
system although the change of parameters, and the feedforward-feedback and fuzzy controller is the better with low and even high frequency disturbance input.

Table 4. Position performance analysis by two control schemes with different mass

| m, kg | L, m | Feedforward-Feedback PID Controller | Feedforward-Feedback (PID)-Fuzzy Controller |
|-------|------|-----------------------------------|--------------------------------------------|
|       |      | OS, % | t, sec | Error, m | OS, % | t, sec | Error, m |
| 1.0   | 0.6  | 17.85 | 6.4    | 0        | 7.4   | 5.3    | < 0.0005 |
| 1.5   |      | 17.57 | 6.5    | 0        | 8.57  | 5.2    | < 0.0005 |
| 2.0   |      | 18.57 | 6.54   | 0        | 8.59  | 5.2    | < 0.0005 |

Table 5. Swinging performance analysis by two control schemes with different mass.

| m, kg | L, m | Feedforward-Feedback PID Controller | Feedforward-Feedback (PID)-Fuzzy Controller |
|-------|------|-----------------------------------|--------------------------------------------|
|       |      | Max, ° | t, sec | Max, ° | t, sec |
| 1.0   | 0.6  | 3.1    | 6.6    | 2.1    | 5.4    |
| 1.5   |      | 3      | 6.7    | 2.0    | 5.11   |
| 2.0   |      | 2.8    | 6.7    | 1.81   | 5.1    |

Table 6. Position performance analysis by two control schemes with different length.

| L, m | m, kg | Feedforward-Feedback PID Controller | Feedforward-Feedback (PID)-Fuzzy Controller |
|------|------|-----------------------------------|--------------------------------------------|
|      |      | OS, % | t, sec | Error, m | OS, % | t, sec | Error, m |
| 0.6  | 1    | 17.85 | 6.4    | 0        | 7.4   | 5.3    | < 0.001  |
| 0.8  |      | 19.0  | 7.2    | 0        | 10.29 | 5.2    | < 0.001  |
| 1.0  |      | 20.55 | 7.3    | 0        | 11.75 | 5.2    | < 0.001  |

5. Conclusion
A forward-feedback controller FFC which is constructed by a feedforward controller and conventional PID is proposed in this study. Then fuzzy technique is added to the system to have a resultant optimal control of forward-feedback-fuzzy FFC controller.

For simulation and performance analysis of the control schemes, the MATLAB-Simulink models have been developed. The gain values of PID or PID-Fuzzy controllers which have been used in this study are achieved using trial and error method and watching the behaviours carried out to be the most favourable. Two proposed fuzzy logic controllers are implemented in this study, one for the displacement and the second for angle. The inputs to these controllers are the displacement error and velocity and the angle error and angular velocity of the pendulum. At the same time, the outputs of these controllers are the forces required to drive the cart.

To demonstrate the proposed method, a continuous low-frequency and high-frequency disturbance input subjected to test the system. The simulation results of the proposed forward-feedback FFC control approach is compared with forward-feedback-fuzzy FFC controller to demonstrate the efficiency of them.

Simulation results prove that the forward-feedback controller is successfully designed and used to move the overhead crane to a desired position while attenuate the payload swinging at the end of the motion. Furthermore, it is noted that the forward-feedback-fuzzy FFC controller enhanced the response of the system (such as minimizing overshoots and expedite settling time) compared with forward-feedback FFC PID-controller even though there is a high-frequency of disturbance input to the system. Finally, neither the effect of mass changes nor the length of the rob changes have been described on the payload swing suppression.
The results of the proposed controller by this research indicates outguess of it with respect to the former researches in this field, where in [3] and [8] the maximum swinging angle was 10° and 57°, respectively, which needs a longer time to be stable, approximately 40 sec for swinging a 0.4 Kg of mass such as in [20]. In [13], they proposed a controller for a small volume crane system, where the length about 0.09 m and small mass, however when they excited their system by a disturbance, it couldn't damp the oscillation quickly.

6. References
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