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Robustness Analysis for a Nonlinear Gantry Crane System Using Fuzzy Logic Controller

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ABSTRACT

Gantry cranes are equipment used for loading and unloading heavy items. They are majorly used in the industries and shipyards to transport heavy loads. Generally, operational requirements for the gantry crane is to move the load with minimum swing angle, high positioning accuracy and with minimum time possible. External and environmental disturbances affects the performance of the gantry crane when in operation. Control of the gantry crane system has over many years attracted many researchers with interest in designing a robust gantry crane system free of swing motions. Several researchers have proposed the use of PID controllers. However, their control methods have limitations among them, being sensitive to disturbances. Thus, for the crane to operate effectively, trolley positioning and swing motion of the load need to be controlled. The main goal of this research is to design a robust control mechanism for the gantry crane system against swing motion due to uncertainties. The gantry crane system has been designed using mathematical modeling with assumption that the load is attached to a trolley using one rope and moves in 2D plane. The robustness analysis of the Fuzzy Logic Controller (FLC) has been simulated in MATLAB/Simulink environment and comparison done with auto-tuned PID controller in environment where external disturbances are present. Various transient response performance indices specifications have been used to determine the effectiveness of the controller model. The final results have demonstrated that FLC is capable of producing better results of minimizing swing motion as compared to PID controllers.

Key words: Gantry Crane, Anti-swing, Position Control, PID Controller and Fuzzy Logic Controller

INTRODUCTION

Material handling and transportation is very important in any manufacturing, construction and shipping industries. Gantry cranes are widely used in such kind of industries. The major applications of gantry crane is to load, transport and unload heavy materials from one place to another. It is therefore necessary to ensure that the transportation is done with high level of safety, accuracy and with minimum time possible. This can only be achieved by controlling the swing motion of the payload and proper positioning of the trolley (Jaafar *et al*, 2015). Generally, the operation of the gantry crane relies on the skills and experience of the operator who controls it manually. This requires a better solution since manual operation by human beings are known to be affected by human errors and fatigue. Consequently, due to difficulties experienced in operating a gantry crane, automation may be a solution to achieve desirable performance.

Feedback control methods such as Proportional-Derivative (PD) and Proportional, Integral and Derivative (PID) control techniques have attracted many researchers for controlling the gantry crane system. However, these methods are sensitive to environmental and external disturbances (Cetin & Iplikci, 2015). Also variations in parameters such as cable length and load mass affects the stability during operation. Controlling position of the trolley by use of PD controllers is ineffective to eliminate steady state error. Similarly, performance characteristics of the PID controller can degrade when actuator reaches saturation state (Yang *et al.,* 2021). Moreover, the design of a classical PID controller is generally based on the parameters and model of the plant to be controlled. Also, the modeling process and parameter identification is tedious and time consuming process (Chopra *et al.*, 2014) This paper considers soft computing methods, among them being Fuzzy Logic Controllers (FLC) to provide a robust mechanism for controlling swing motion of gantry crane due to its ability to mimic human behavior. Also, FLC covers wide operating range of conditions and also its ability to operate in noisy environment and with disturbances of different nature (Almutairi *et al*, 2016). The expected impacts include addressing the problem of time wastage, positioning accuracy, minimum swing angle and high safety.

Approaches on FLC for a gantry crane system

Fuzzy logic controller system for controlling trolley position and swing motion of an overhead crane was proposed based on single input rule modules (SIRMs) (Qian *et al.,* 2015). The designed system was robust to variations in rope lengths. However, the design system required many inputs hence complex in design and high possibility of causing errors.

Fuzzy logic controller design using two rules was proposed (Sakalli *et al.*, 2020). The final results showed that by use of FLC, the crane could travel smoothly to the destination within a short period and with small swing angle. However, no general procedure for robustness was discussed in the results

An automatic control system using FLC for a 3 Degree Of Freedom (D.O.F) gantry crane was proposed (Abdallah *at al.*, 2011). The aim was to design a simple system using fuzzy logic for trolley position control and reduced swing motion of the payload. The performance comparison was done between PID controller and FLC. The overall results showed that performance of FLC is much better as compared to PID controller in terms of settling time, also FLC is simple in design, has simple algorithm and requires less mathematical computation. However, the project did not consider changes due to uncertainties caused by external disturbances.

Comparative analysis for optimal control and fuzzy logic controller for an overhead crane was proposed (Ranjbari *et al.,* 2015). The aim was to compare optimal control methods and FLC in the keeping off any swing motion of the crane. The simulation was performed using MATLAB. Comparative analysis for the stability showed that FLC is capable of dampening the oscillations and minimizing load angle as compared to other optimal control methods. Gantry crane control system using fuzzy logic with experimental verifications was proposed (Almutairi *et al*, 2016). The main objective was to design a controller system capable of controlling gantry crane even when some parameters are unknown.

The comparative analysis mainly focused on FLC techniques to dampen the oscillation of a gantry crane system. According to the study, the fuzzy logic controller is seen as a better option for damping the oscillation when the system is nonlinear and due to uncertainties. Thus, the FLC design can be compared with auto-tuned PID controller to validate its performance in controlling the swing motion of gantry crane when the external disturbances are present.

METHODOLOGY

The research is based on possibilities of producing a robust system capable of minimizing swing motion of Gantry cranes useful in shipping industry to improve efficiency. The developed system considers operation of the gantry crane when external disturbances are present. The study is based on mathematical modeling of a gantry crane and simulation done on MATLAB/Simulink environment.

Mathematical Modeling of a Nonlinear Gantry Crane System

The research considers the Lagrange's equation of motion to solve equations of a payload hanging on a trolley. Lagrange's equations are well known to formulate solutions of motion of mechanical system with multiple degrees of freedom (Stutts *et al.*, 2017). It consists of a trolley moving along a track and translates in a horizontal plane. A payload is attached and suspended from a trolley by a cable. An illustration representing gantry crane is shown in Figure 1(Shebel *et al.* 2011).

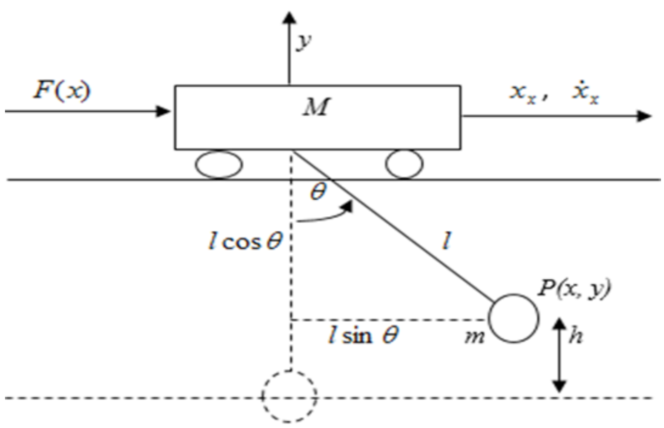

Figure 1. Model of a gantry crane in pendulum motion (Shebel *et al.* 2011).

Where,

M Represents the mass of the trolley/cart

m Is the mass of the payload

F_x Is the driving force to the trolley in Newton

x_x is the position of the trolley

$\dot{x}_x$ Represents the velocity of trolley

θ Denotes rope swing angle in degrees

h Height of payload above reference height

l Is the length of the rope

The Lagrange's equations of motion can be realized by considering a body having translational kinetic energy and oscillating energy using the following assumptions:

i. The cable connecting payload and trolley is inelastic
ii. The trolley attached to the payload is moving in a 2D plane
iii. The mass of the load is constant and hangs on one rope
iv. The trolley position is known

The dynamic equations of kinetic and potential energy of a free body diagram can be obtained using Lagrange equation of motion shown in equation (1) as: (Vrabel *et al.*, 2021).

$$L = T - V = \frac{M}{2}\dot{x}^2 + \frac{m}{2}(\dot{x}^2 + 2l\dot{x}\dot{\theta}\cos\theta + l^2\dot{\theta}^2) - mgl(1-\cos\theta) \quad (1)$$

The generalized Euler- Lagrange's equation for a conservative and non-conservative systems can be represented by equation (2) and equation (3) respectively

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_k}\right) - \frac{\partial L}{\partial q_k} = 0 \quad (2)$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_k}\right) - \frac{\partial L}{\partial q_k} = F_x \quad (3)$$

Where,

q_k Is the generalized coordinates (x, θ)

$\dot{q}_k$ Is the generalized velocity ($\dot{x}, \dot{\theta}$)

F_x Is the translational force of the cart/trolley

From the Lagrange's equation of motion the final equations can be expressed as:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) - \frac{\partial L}{\partial x} = (M+m)\ddot{x} + ml\ddot{\theta}\cos\theta - ml\dot{\theta}^2\sin\theta = 0 \quad (4)$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}}\right) - \frac{\partial L}{\partial \theta} = ml^2\ddot{\theta} + ml\ddot{x}\cos\theta + mgl\sin\theta = 0 \quad (5)$$

Therefore, the equation for the payload oscillation and translation motion of the trolley can finally be expressed by equations (6) and (7) respectively as:

$$m(\ddot{x}\cos\theta + l^2\ddot{\theta} + g\sin\theta) = 0 \quad (6)$$

$$(M+m)\ddot{x} + ml(\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta) = F_x \quad (7)$$

Generally, in modeling gantry crane system, the driving force of the trolley in x-axis (F_x) is driven by a DC motor shown in Figure 2 below (Hussien *et al.*, 2015).

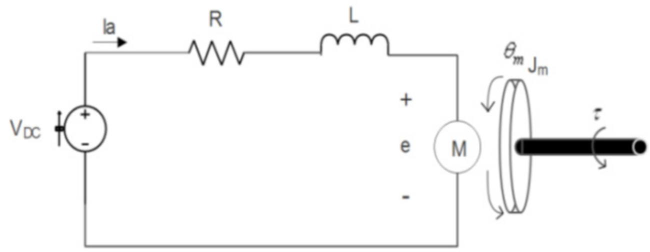

Figure 2. Servo DC motor system (Hussien *et al*, 2015)

The crane servo system consists of pulley mechanism, which translates torque of motor shaft into trolley motion (Solihin *et al.*, 2010). The force driving DC motor of the trolley is expressed as (Hussien *et al.*, 2015):

$$F_x = \frac{V k_g k_t}{R r_p} - \frac{k_e k_t}{R r_p^2}\dot{x} \quad (8)$$

Where,

i. $\dot{x}$: The velocity of trolley in meters/sec,

ii. R : The motor resistance in Ohms (Ω)

iii. F_x :The driving force to the trolley in Newton

iv. k_e :Electric constant

v. k_t : Torque constant of the servo motor

vi. k_g Gear box ratio

vii. V : Voltage of the motor in Volts

viii. r_p :Radius of the pulley in meters

Equation (7) and (8) yields expression (9) below:

$$(M+m)\ddot{x} + ml(\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta) = \frac{VK_g k_t}{R_p} - \frac{k_e k_t}{R_p^2}\dot{x} \quad (9)$$

This research proposes modeling nonlinear mathematical equations for controlling gantry crane system. This can be achieved by assuming that swing angle will remain small as possible, therefore, $\cos\theta \cong 1$, $\sin\theta \cong \theta$ (DeMoura *et al.*, 2013). Swing angle can only be at maximum when θ is at $\ddot{\theta}$. Therefore, at maximum angle, $\ddot{\theta} \cong x$. Thus, the following expressions shown in equations (10) and (11) can be obtained as:

$$(M+m)\ddot{x} + mlx = \frac{VK_g k_t}{R_p} - \frac{k_e k_t}{R_p^2}\dot{x} \quad (10)$$

$$\ddot{x} + \frac{k_e k_t}{R_p^2(M+m)}\dot{x} + \frac{ml}{(M+m)}x = \frac{VK_g k_t}{R_p(M+m)} \quad (11)$$

By assumptions that the mass of the payload m, is very small as compared to the mass of the trolley (M), hence neglected. Therefore, the two equations (10 and 11) can be expressed by equations (12) and (13) respectively as:

$$\ddot{x} + \ddot{\theta} + g\theta = 0 \quad (12)$$

$$M.\ddot{x} + \frac{K_e K_t}{R_p^2}\dot{x} + k = \frac{VK_g K_t}{R_p} \quad (13)$$

Representation of equations (12) and (13) in Laplace complex domain at zero initial conditions can yield the following transfer functions:

$$\frac{\theta(s)}{X(s)} = \frac{-s^2}{ls^2 + g} \quad (14)$$

$$\frac{X(s)}{V(s)} = \frac{k_0}{As^2 + Bs + C} \quad (15)$$

Where,

$$k_0 = \frac{k_t k_g}{lRr_p} \quad (16)$$

$$A = \frac{M}{l} \quad (17)$$

$$B = \frac{k_e k_t}{lRr_p^2} \quad (18)$$

$$C = 1 \quad (19)$$

By finding the step response for the general second order system, the transform of the response of equation (15) can be expresses as the transform of the input times the transfer function as shown in equation (20 and 21) below (MouraOliveira *et al.*, 2012):

$$X(s) = \frac{k_0.V(s)}{(As^2 + Bs + C)} \quad (20)$$

$$X(s) = \frac{1}{s}\cdot\frac{k_0}{(As^2 + Bs + C)} \quad (21)$$

Where,

$\frac{1}{s}$ Represents step input = $V(s)$

The gantry crane system modeling parameters for the expressions (10 to 21) were identified from system dynamics and identification materials for the gantry crane (Almutairi et al., 2016; Solihin *et al.*, 2010; Jaafar *et al.*, 2013; Bruins *et al.*, 2010; Khatamianfar *et al*, 2019). Table 1 below shows the parameters of the crane used in developing the mathematical equations.

Table 1. Parameterization of gantry crane model

Parameter	Description	Value
l	Cable length	$0.6\ m$
M	Mass of trolley	$1\ kg$
m	Load mass	$0.236\ kg$
g	Gravitational Acceleration	$981\ m/s^2$
r	Radius of pulley	$2\ cm$
R	Motor resistance	$0.944\times 10^{-3}\ \Omega$
k_t	Torque constant	$0.7\ N.m/A$
k_e	Electric constant	$0.007\ V/rad$
k_g	Gear box ratio	3.7

The final expressions representing gantry crane system for position of the trolley and payload oscillations are as shown in equations (22) and (23) respectively.

$$X(s) = \frac{8\ .2}{s(0.018s^2 + 0.236s + 1)} \quad (22)$$

$$\frac{\theta(s)}{X(s)} = \frac{-s^2}{0.6\ s^2 + 981} \quad (23)$$

Fuzzy Logic Controllers (FLC) Design

FLC is among the most recent control method whose popularity is growing fast. Fuzzy logic mimics human beings in making decision (Ansari *et al.*, 2015). The basic design procedures adopted includes: development of fuzzy rules, fuzzification and defuzzification process. FLC designed model was simulated based on 'If- Then' rules which mimic the human being way of reasoning (Cingolani *et al.*, 2013). These rules are adopted from experienced operator by considering the target position, actual position and the crane velocity during operation. For the position control, the following dynamic variables of the crane motion are considered when generating rules (Pham, 2020).

- When the trolley position is positive with respect to the origin, the trolley is accelerated negatively causing it to move in negative direction towards its destination.
- When the trolley position is negative with respect to origin, it should be accelerated positively thereby causing it to move in positive direction towards the destination.
- When the trolley velocity is positive with respect to the origin, acceleration force in negative direction is required to reduce the velocity from positive to zero.
- In-case the trolley velocity is in negative direction, acceleration in positive direction is required to increase the velocity from negative to zero.

Trolley position control using FLC was designed based on the above linguistic variables. The input and output linguistic variables for error and error rate put into consideration are: Positive (P), Zero (Z) and Negative (N). Table 2 shows the linguistic variables used in generating fuzzy rules for position control.

Table 2. Fuzzy rules for position control

Error rate/Error		Error rate $\dot{e}(t)$		
		P	Z	N
Error $e(t)$	P	P	P	P
	Z	N	Z	P
	N	N	N	N

Similarly, the swing angle can be controlled by using the dynamic variables of the crane in motion. These include (Pham, 2020):

- When the swing angle is positive with respect to the origin, trolley should be accelerated positively. The force of inertia due to the load will cause the rope to rotate in clockwise direction, therefore reducing the swing angle towards zero position.
- When the swing angle is negative with respect to the origin, the trolley motion should be decelerated. This will cause the rope to rotate in counterclockwise direction causing the swing angle to reduce towards zero position.
- When the angular velocity is positive with respect to the origin, the trolley should be accelerated positively so that the angular acceleration becomes negative. Thereafter the trolley should be decelerated so that the angular velocity becomes positive toward zero position.

The payload oscillation control was designed based on fuzzy rules developed in Table 3 below. The linguistic variables considered in the design includes: Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Big (PB).Thus, from the above information, the fuzzy rules for anti-swing were developed. This is tabulated in the Table 3 where a total of 25 rules were generated.

Table 3. Fuzzy rules based on anti-swing

Swing angle rate/ Swing angle		Swing angle rate $\dot{\theta}$				
		PB	PS	Z	NS	NB
Swing angle θ	PB	PB	PB	PB	PB	PB
	PS	PB	PS	PS	PS	PS
	Z	PB	PS	Z	NS	NB
	NS	NS	NS	NS	NS	NB
	NB	NB	NB	NB	NB	NB

Fuzzy logic controller membership functions

The linguistic rules are used to design input membership values which gives the weighting factors that determines the influence of the output sets. The design model adopted triangular membership functions due to simplicity (Ali *et al.*, 2015). From Tables 2, the membership functions for error, error rate were adopted as the inputs while, power as the output. The universe of discourse adopted for error is $-80\ to\ 80\ cm$, for error rate is -$15\ to\ 15 cm/s$ and for power is$-1.35\ to\ 1.35\ watts$.

Similarly, from Table 3, the membership functions for swing angle and swing angle rate were adopted as the inputs, while Power as the output. The universe of discourses was considered to be from $-1\ to\ 1\ rad$ for swing angle, $-2\ to\ 2\ cm/s$ for swing angle rate and $-1.5\ to\ 1.5\ volts$ for power.

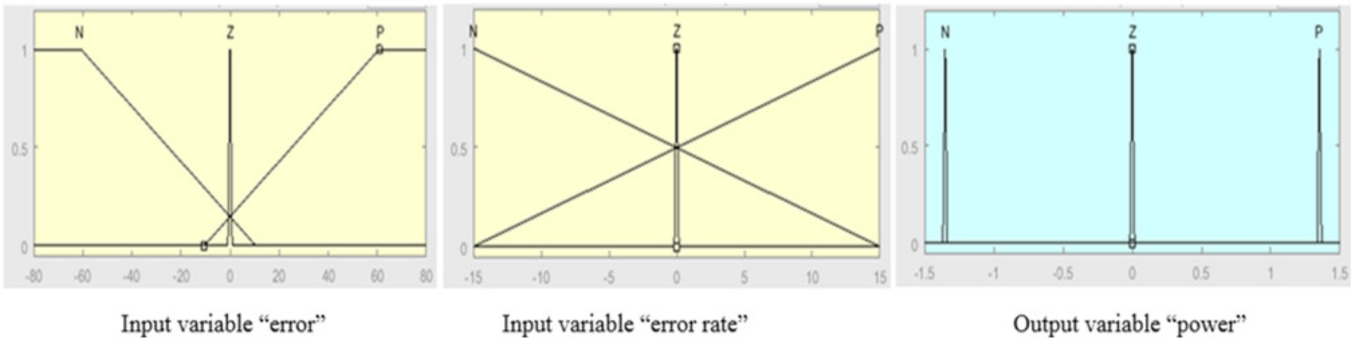

Figure 3. Membership functions for position control

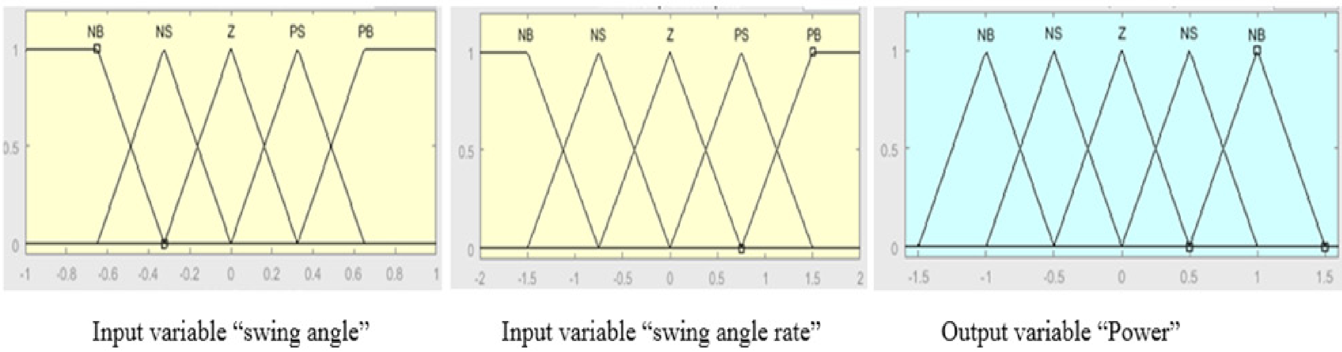

Figure 4. Membership functions for anti-swing control

RESULTS

System model design

Gantry crane model has been simulated in a closed loop system using mathematical model. The mass and inertia properties of the system have been put into account. The performance of the auto-tuned PID and FLC has been simulated and comparison done in the MATLAB/Simulink environment. The design for position and anti-swing control was simulated by employing an input step function as a reference for the desired signal. The simulation model in MATLAB/Simulink is as shown in Figure 5 below.

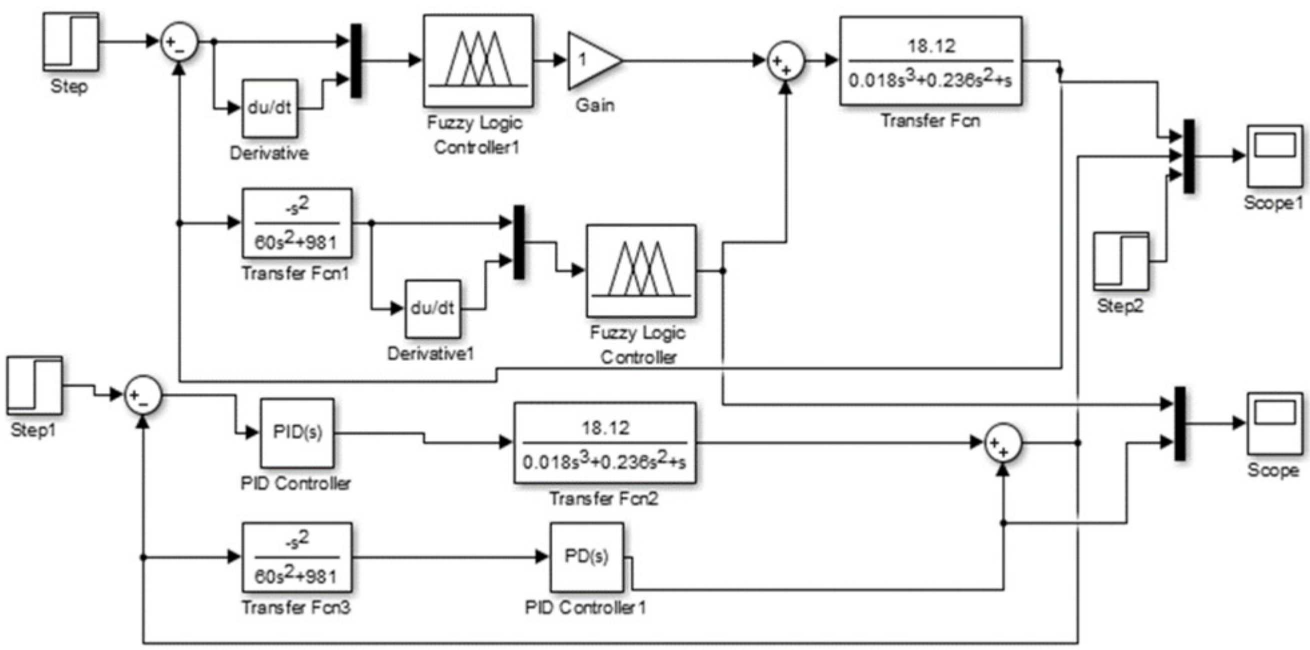

Figure 5. FLC and PID controller design in MATLAB/Simulink

Control simulation responses

The output response results for position control and anti-swing control for FLC and auto-tuned PID controllers were simulated at a constant rope length of 60cm. The results of the two controllers were compared considering the performance indices such as; settling time, Overshoot, Steady state error and Peak time for position control, while overshoot and settling time were considered for anti-swing control.

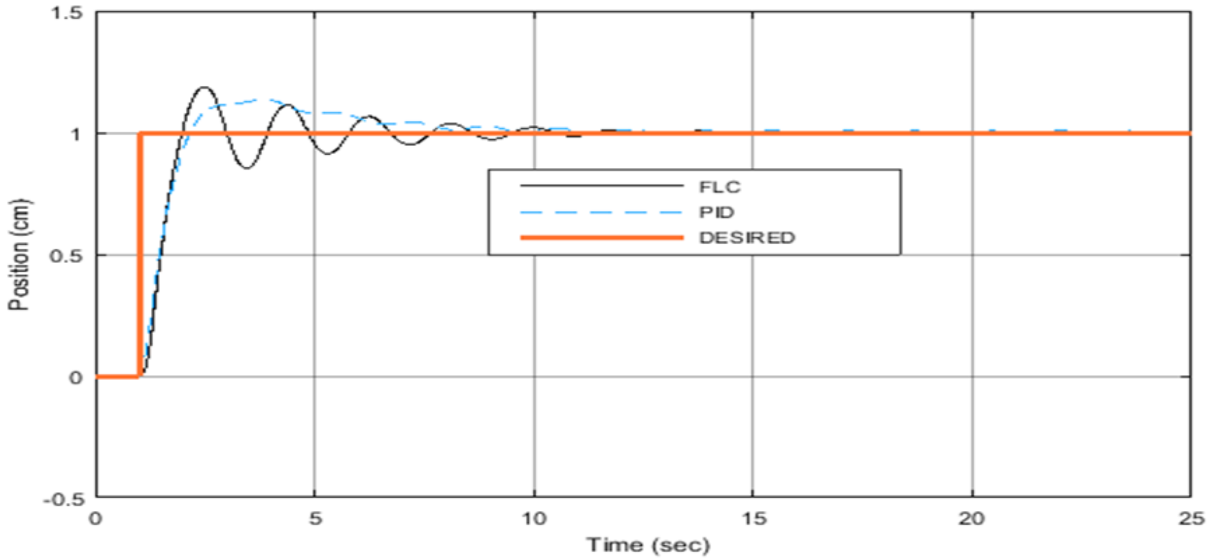

Figure 6. Position control response for FLC and auto- tuned PID controller

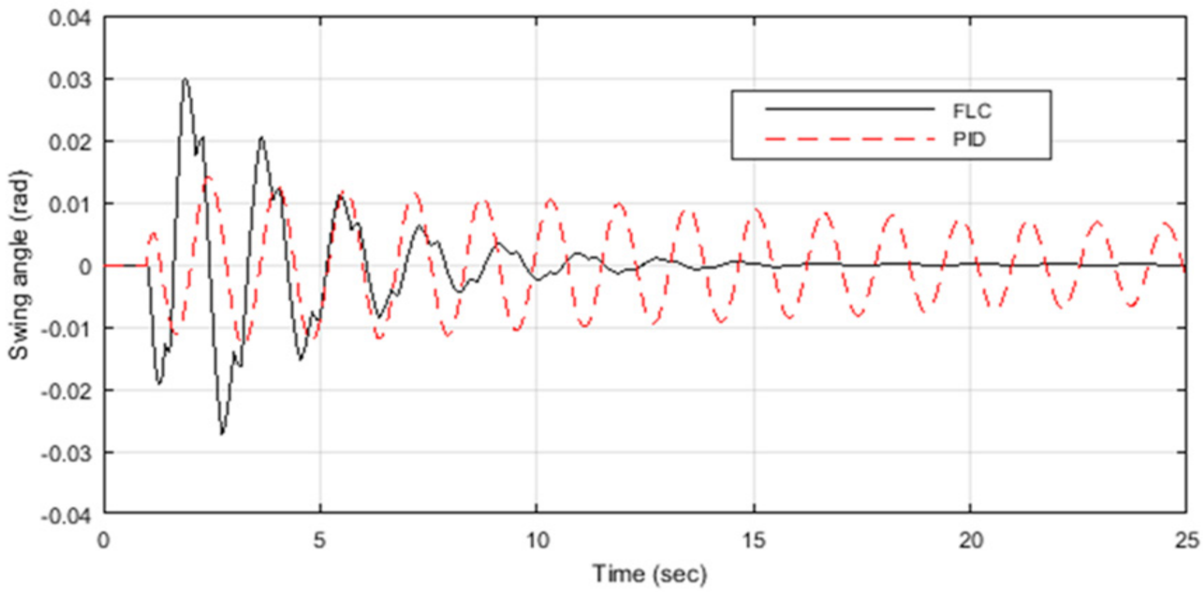

Figure 7. Payload oscillation response for FLC and auto- tuned PID controller

The main goal of position control in this research paper is to ensure the trolley of the gantry crane takes minimum time possible to settle and with high positioning accuracy. The results illustrated in Figures 6 and Figure 7 shows that FLC can produced better response than auto-tuned PID controller.

System reaction to disturbance

Environmental disturbances such as wind, motion and vibration are some of the key disturbances which have been identified as the major sources which affects the operation of the gantry crane. The simulation has been done by injecting white noise with power density of 1×10^{-3} 1×10^{-3} Watt per hertz. The performance of the auto-tuned PID controller and FLC have been simulated and comparison done to determine the better controller model that rejects disturbances.

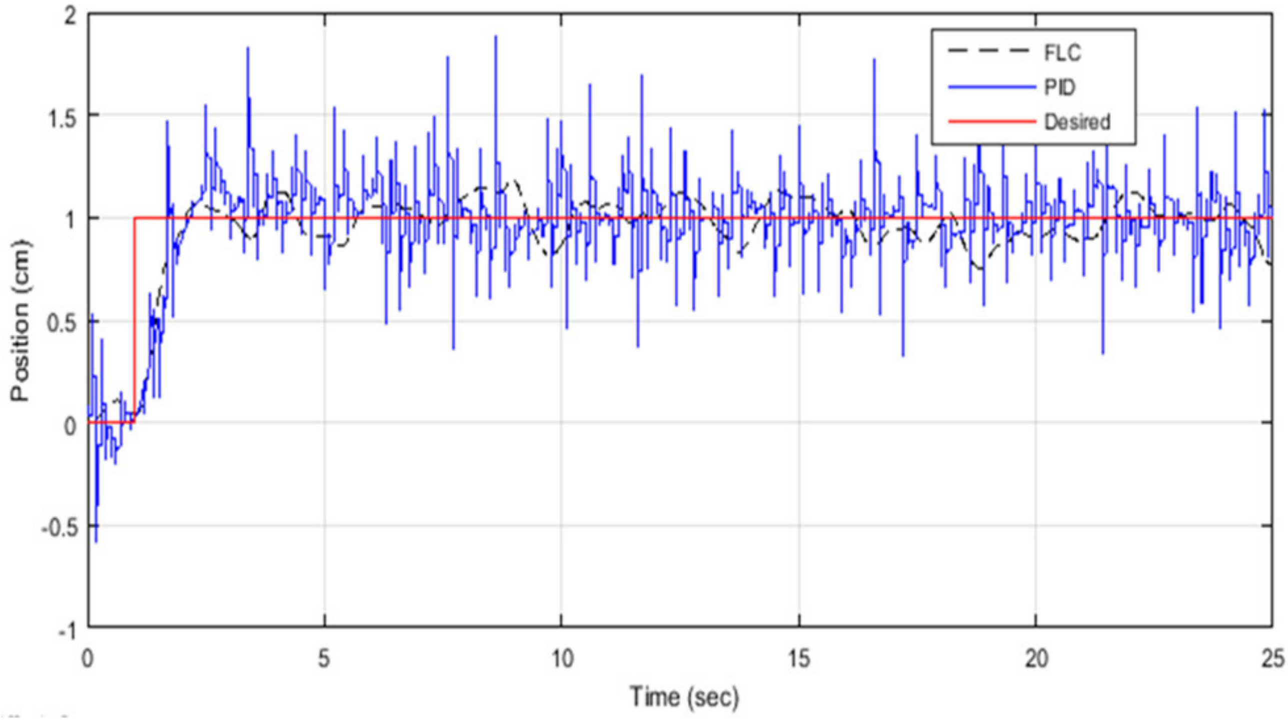

Figure 8. Position control response at 1×10^{-3} Watt per Hz

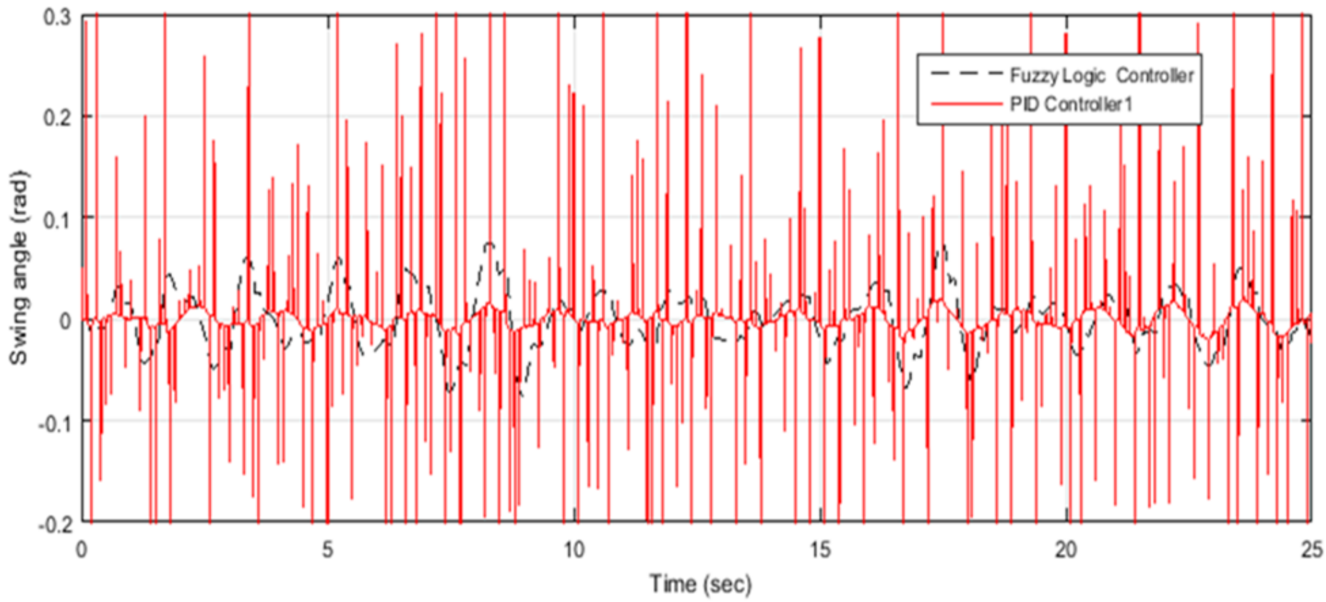

Figure 9. Anti-swing control response at 1×10^{-3} watt per Hz

The gantry crane position control and ant-swing control performance responses to disturbances has been shown in Figures 8 and 9. The illustrations are simulated to show comparison between FLC and auto-tuned PID to reject the noise present when the crane is in operation. From the simulations, the FLC is showing better responses to reject noise as compared to PID controller.

DISCUSSION

The two controller models have been simulated and comparison done based on the time response performance indices such as: settling time, steady state error, peak overshoot and peak time for position control while settling time and amplitude were used to determine the better model for anti-swing control. The disturbance rejection controller models developed considers steady state error for the position control and also anti-swing control. This is to determine better performance in terms of accuracy and efficiency with respect to time.

Table 4. Position control results for FLC and PID without noise

Controller	Reference (cm)	Overshoot (%)	Settling time (sec)	Peak time (sec)	Steady state error (cm)
PID	60	0.18	17	3.9	0.02
FLC	60	0.22	12	2.28	0

Table 5. Anti-swing control results for FLC and PID without noise

Controller	Reference (cm)	Amplitude (cm)	Settling time (sec)
PID	60	0.01	30<
FLC	60	0.027	18

Table 6. Position control results for FLC and PID at different noise

Controller	Reference (W/Hz)	Steady state error (cm)
PID	1×10^{-3}	0.9
FLC	1×10^{-3}	0.4

Table 7. Anti-swing control results for FLC and PID at different noise

Controller	Reference (W/Hz)	Steady state error (cm)
PID	1×10^{-3}	0.75
FLC	1×10^{-3}	0.016

CONCLUSION

The two controllers have been simulated to evaluate their robustness ability to minimize swing motion of a gantry crane. The performance of the two controllers has been evaluated by simulating the system in noisy environment to determine the suitability for implementation. The evaluation was based on considering performance indices analyzed in tables to compare their performance. The general results showed that the performance of FLC was better compared to that of auto-tuned PID controller.

The soft computing methods have proved that they can produce better results as compared to conventional controllers. The hybrid between FLC and ANN need to be put into consideration for further research.

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