Performance Comparison between *LQR* and *FLC* for Automatic 3 DOF Crane Systems

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Abstract

The 3 Degree-of-Freedom (DOF) crane represents one of the most widely deployed real-world platforms in the world today. It uses levers and pulleys for gripping, lifting and moving loads horizontally, as well as lowering and releasing the gripper to the original position. Hence the system produces swing angle which need to be controlled so that the payload could be transferred efficiently. The existing 3 DOF systems used conventional Linear Quadratic Regulator (LQR) controller to control the position and swing angle. This project report proposed the usage of Fuzzy Logic Controller (FLC) in place of LQR controller. FLC has a simpler and practical design approached. It avoids laborious mathematical formulation and computation thus reducing operating time. The FLC performance for position control and anti-swing control are compared with LQR controller using MATLAB simulation. The simulation results showed, under laboratory limitation, that FLC performed better compared to the conventional LQR controller.

Keywords: *crane system, linear quadratic regulator, fuzzy logic control, performance*

1. Introduction

Typically industrial cranes manipulated lever and pulley for gripping, lifting and moving loads horizontally. These cranes employ very strong structures for lifting heavy payloads in factories, construction site, and ships and in harbours. These tasks are performed with the aid of hoisting mechanism that works as an integral part of the crane. Until recently, cranes were manually operated but as it became larger need to move at high speeds, their manual operation became difficult. In factories, cranes speed up the production processes by moving heavy materials to and from the factory as well as moving the products along production lines. In building construction, cranes facilitate the transport of building materials to high and critical spots. Three degree of freedom (3DOF) crane was included in the overhead crane types and is widely used in industry for moving heavy objects. However, overhead cranes have serious problems such as the acceleration and deceleration which will induce undesirable load swing which degrades work efficiency and compromises safety issues. From a dynamics point of view, the overhead cranes are under actuated mechanical systems. It has fewer control inputs than the degrees of freedom, which complicate the related control problems. First attempt to control the position and swing angle of the system is done using classical controller, the Linear Quadratic Regulator (LQR), which involved complex mathematical computation. This paper reports on the performance comparison between LQR and the proposed Fuzzy Logic Controller (FLC) when applied to overcome the problem of exact position and swing effect. The study focussed on controlling the jib, which is one of subsystem of the crane.

The paper is organized as follows. Section 1 explains the overall background of the study. Section 2 will cover the literature review of the controller which is based on Linear Quadratic Regulator and Fuzzy Logic Controller. Section 3 present the LQR modeling and Section 4 described the design of the Fuzzy Logic Controller. Modeling of the Gantry was described in Section 5. Section 6 decribed the performance of the LQR and FLC system and Section 7 concludes the paper.

2. Related Work

The 3DOF crane [13, 14, 15, 16] represents one of the most widely deployed heavy machinery in the real-world platforms today. The task of the 3 DOF crane is to move the payload from one point to another. Hence the system produces swing angle which need to be controlled so that the payload will be transferred quickly, effectively and safely. Traditionally LQR controller was employed to control the position and swing angle but involved complex and time consuming mathematical computation. The Fuzzy Logic Controller (FLC) was reported to be the potential replacement to the LQR [1, 2, 3]. The design, methodology and algorithm of the FLC is expected to be very much simpler. The model and parameters of the 3DOF crane systems is disregard when using FLC. Hence it is also known as a non non-model based controller, which can fulfil the design methodology for achieving high performances. Ho-Hoon Lee *et al* [4] presented a new fuzzy logic anti swing control for industrial three dimensional overhead cranes. The control consists of a position servo control for aligning crane position and fuzzy logic control for load swing suppression. D. M. Dawson *et al* [5] designed two nonlinear energy based coupling control procedure that increases the coupling between pendulum position and the gantry. H.M. Omar [6] designed a controller with robust, fast and practical for gantry and tower cranes. However, the result showed that, fuzzy controller produced smaller transfer time and overshoot but with rather high swing angles. This response could be improved by proper adjusting the parameter of the membership functions. J. Jalani *et al* [7] designed a more robust FLC for an Intelligent Gantry Crane System, which proved that FLC is better compared to the conventional controller. However, the application of FLC for gantry crane and their parameter is totally different from the 3DOF crane systems. M. Z. Othman [8] proposed a rough controller which is based on mathematical computation to control the overhead travelling crane. However, the result showed that the quality index for both controllers does not differ very much. Hence, FLC was chosen as a comparison to the conventional LQR controller for 3DOF Crane system.

3. Linear Quadratic Regulator (LQR) System Modeling

The technique of optimal control is concerned with the operation of a dynamic system with minimum cost. This linear system will be model using Linear Quadratic Regulator. It is a well-known design technique that provides practical feedback gains. Linear Quadratic Regulator deals with state regulation, output regulation and tracking [9] with quadratic performance index or measure. In the LQR controller, there are three elements that should be considered in designing the controller; Error Weight Matrix(Q(t)), Control Weight Matrix(R(t)) and the Control Signal(u(t)). In order to keep the error as small as possible, the Error Weight Matrix must be positive and semi definite. The Control Weight Matrix should be positive definite. The Control Signal is important to obtain the optimum loop configuration.

For finite horizon, the continuous-time linear system is described as:

$$\dot{x} = Ax + Bu \tag{1}$$

with a quadratic cost function defined as

$$J = \frac{1}{2} x^T(t)F(t)x(t) + \int_0^T (x^T Qx + u^T Ru)dt \tag{2}$$

The feedback control law that minimizes the value of the cost is stated as,

$$u = -Fx \tag{3}$$

where F is given by $F = R^{-1}B^T P$ (4) and ***P*** is found by solving the continuous time algebraic Ricatti equation (CARE). Meanwhile for infinite horizon, a discrete time linear system described as,

$$x_{k+1} = Ax_k + Bu_k \tag{5}$$

with a performance index refined as

$$J = \sum (x_k{}^T Qx_k + u_k{}^T Ru_k) \tag{6}$$

and the optimal control sequence minimizing the performance index is given by $u_k = -Fx_k$, where $F = (R + B^T PB)^{-1} B^{-1} PA$ and ***P*** is the solution to the discrete time algebraic Ricatti equation (DARE). For 3DOF crane system, the feedback loop was used to control the position of the trolley while dampening the motions of the payload. LQR compensator is used to regulate the position in the finite-horizon. By assuming full-state feedback, the LQR algorithm can be used to calculate the control gain. Augment the jib system state in as follows,

$$\zeta^T = \left[x_j(t), \gamma(t), \frac{d}{dt} x_j(t), \frac{d}{dt}\gamma(t), \int x_j(t)dt \right] \tag{7}$$

to include a cart position integrator. Next, using the control law $u_j = K_j \zeta$. The LQR method is used to minimize the cost function

$$J = \int_0^\infty x(t)^T Qx(t) + u_j(t)^T Ru_{j(t)} dt \tag{8}$$

where Q and R are weighting matrices and given that Q and R as:

$$Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{ and } R = 0.1. \tag{9}$$

However as previously mentioned, there are only two measured states in the gantry system - the linear trolley position and the pendulum angular position. Therefore, the actual implemented controller is of the form $u_j = -K_j \zeta_{j,e}{}^T$ where,

$$\zeta_{j,e}{}^T = \begin{bmatrix} x_{j,f}(t) - x_{j,df}(t), \gamma_f(t), \\ \left(\frac{d}{dt} x_{j,df}(t)\right) - \left(\frac{d}{dt} x_{j,df}(t)\right), \\ \frac{d}{dt}\gamma_j(t), \int x_{j,f}(t) - x_{j,df}(t)dt \end{bmatrix} \tag{10}$$

is the estimated error state. The $x_{j,f}$ and $x_{j,df}$ states are the filtered measured position of the trolley and the filtered trolley position setpoint. These are both passed through the low-pass filter called $H_x(s)$. The $\frac{d}{dt}x_{j,f}(t)$ state is the filtered derivative of the trolley position after being processed by the high-pass filter $D_x(s)$. The filtered trolley velocity setpoint, $\frac{d}{dt}x_{j,df}(t)$ is actually a calculated trajectory that is only passed trough a low-pass filter. Similarly for the pendulum, the states $\gamma_f(t)$ and $\frac{d}{dt}\gamma_j(t)$ are the filtered pendulum angle and the filtered pendulum velocity after being passed through the low-pass filter $H_\gamma(s)$ and the high-pass filter $D_\gamma(s)$ respectively.

4. Fuzzy Logic Control System Modeling

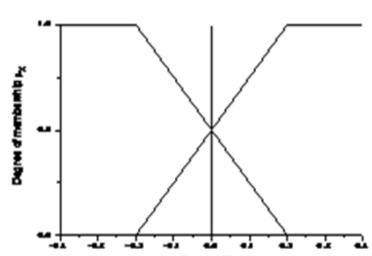
The FLC consists of input fuzzification which converts controller input into information that the inference mechanism can easily be used to activate, fuzzy control rules (a set of IF-THEN rules), fuzzy inference and output defuzzification which converts the conclusions of the inference mechanism into actual outputs for the process [12].

4.1 Membership Functions

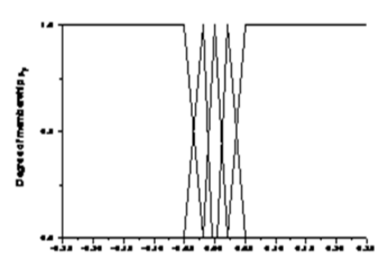
The fuzzy sets are well defined as shown in the Figure 1, where positive (P), zero(Z) ,negative (N) represents the membership function for error and error rate and positive big (PB), positive small (PS), zero (Z), negative small (NS) and negative big (NB) represents the membership function for output of position control. The universe of discourse is from -0.4 to 0.4 m for error, -0.2 to 0.2 m/s for error rate and -7 to 7 V for output voltage. Meanwhile, membership functions for error, error rate and output voltage of anti swing control consist of positive big (PB), positive small (PS), zero (Z), negative small (NS) and negative big (NB) as shown in the Figures 2. The universe of discourse is from -0.25 to 0.25 rad for error, -0.15 to 0.15 rad/s for error rate and -7 to 7 V for output voltage.

4.2 Fuzzy Rule Base

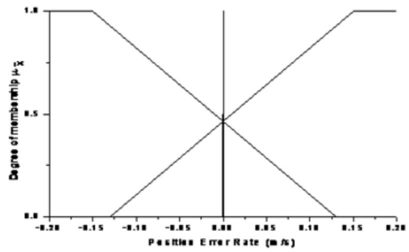
Fuzzy control rules for constant height of the payload are shown in the Table 1 and Table 2 which consist of five membership functions of output voltage. The control rules have been designed based on operator's knowledge and experienced, for example when the swing angle is NS and the swing angle change is Z, then NS of voltage is needed to control the load swing.



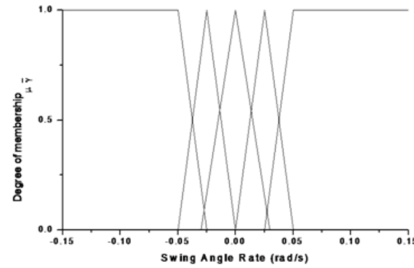
a) Input membership function of position error.



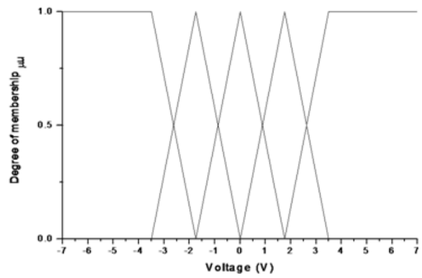
a) Input membership function of swing angle



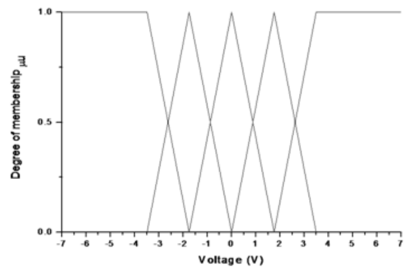
b) Input membership function of position error



b) Input membership function of swing angle rate



c) Output membership function



c) Output membership function

Figure 1. Membership Function of Position Control

Figure 2. Membership Function of Swing Control

4.3 Fuzzy Inference and Defuzzification

The Fuzzy inference for position and anti-swing control has adopted the Mamdani's Min-Max method is computed as $\mu_u = \vee\lfloor \mu_x \wedge \mu_{\bar{x}} \rfloor$ and $\mu_u = \vee\lfloor \mu_\gamma \wedge \mu_{\bar{\gamma}} \rfloor$, where $\wedge$ and $\vee$ denote the minimum and maximum operators respectively while μ_x, $\mu_{\bar{x}}$ and μ_u denote degree of memberships of the error, error rate and output voltage for position control. The variables, μ_γ, $\mu_{\bar{\gamma}}$ and μ_u represent error, error rate and output voltage for anti swing control respectively. The Centre of Area (COA) technique was adopted as the defuzzification process.

Table 1. "position" matrix

$x/\Delta x$	P	Z	N
P	PB	PB	PS
Z	NB	Z	PB
N	NS	NB	NB

Table 2. "angle" matrix

$\gamma/\Delta\gamma$	PB	PS	Z	NS	NB
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

5. Modeling the Gantry System

The system is modeled as a two-dimensional linear gantry. The payload is positioned at a fixed height and the angle is also fixed at about α degree, which is the motion perpendicular to the jib length. It is assumed that the payload only rotates with an angle γ. The trolley is suspended on a linear guide, fastened to a motorized belt-pulley device. When the current in the DC motor, $I_{m,j}$ is positive, the trolley moves away from the tower, towards the end of the jib which is defined as positive velocity. The position of the trolley, x_j increases positively as shown in Figure 3. The payload is connected to the trolley via steel cable. For rigid cable the payload could be modeled as a suspended pendulum. When the trolley goes positive towards the right, the pendulum angle γ, turns clockwise, shown in Figure 4, which is known as positive rotational velocity. The position of the payload's center of mass with respect to Cartesian coordinates system is given as, $O_{x_0 y_0}$ is $x_p = x_j(t) - l_p \sin(\gamma(t))$ and $y_p = -l_p \cos(\gamma(t))$. The Lagrange method is used to find the nonlinear dynamics of the system. The non-linear system equations are also linearized and represent in the state space format. Ignoring the rotational kinetic energy from the pendulum, the linear state-space system of the 3-DOF gantry system is $\frac{\partial}{\partial t} x = Ax + Bu$ and $y = Cx + Du$, where $x^T = \left[x_j(t), \gamma(t), \frac{d}{dt} x(t), \frac{d}{dt} \gamma(t) \right]$ and the state space matrices are given as:

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -\dfrac{m_p r_{j,pulley}{}^2 g}{m_{trolley} r_{j,pulley}{}^2 + J_\psi K_{g,j}{}^2} & 0 & 0 \\ 0 & -\dfrac{g\left(m_{trolley} r_{j,pulley}{}^2 + m_p r_{j,pulley}{}^2 + J_\psi K_{g,j}{}^2\right)}{l_p\left(m_{trolley} r_{j,pulley}{}^2 + J_\psi K_{g,j}{}^2\right)} & 0 & 0 \end{bmatrix} \tag{11}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ \dfrac{r_{j,pulley} \eta_{g,j} K_{g,j} \eta_{m,j} K_{t,j}}{m_{trolley} r_{j,pulley}{}^2 + J_\psi K_{g,j}{}^2} \\ \dfrac{r_{j,pulley} \eta_{g,j} K_{g,j} \eta_{m,j} K_{t,j}}{l_p\left(m_{trolley} r_{j,pulley}{}^2 + J_\psi K_{g,j}{}^2\right)} \end{bmatrix} \tag{12}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \qquad D = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{13}$$

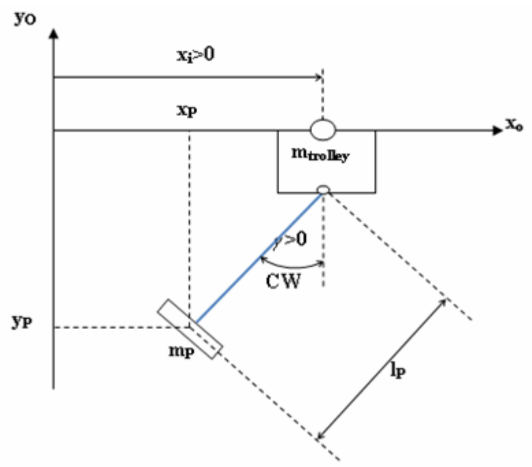


Figure 3. Free Body Diagram of jib System

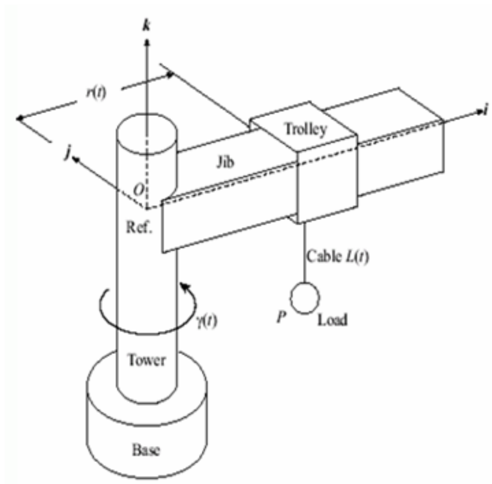


Figure 4. Model of 3DOF Crane

The parameters used in the model are given in the Table 1. This system can then be used to develop a state-feedback control system. As described by the C matrix, the only measured states are the trolley position, x_j and the angle of the pendulum, γ.

6. Performance Analysis

In order to test the performance of the two kinds of controllers, MATLAB and its Fuzzy Logic Toolbox simulink are used [17]. System performance with LQR and FLC are compared via simulation. Initially the trolley needs to be set at the centre position. The trolley can move up to ±400cm or 0.4m. Safety precaution is done by having the limit at the end of the jib. Hence, 400cm is chosen to be a reference maximum position for this simulation. Initial test was done without the controller.

6.1 System Performance without Controller

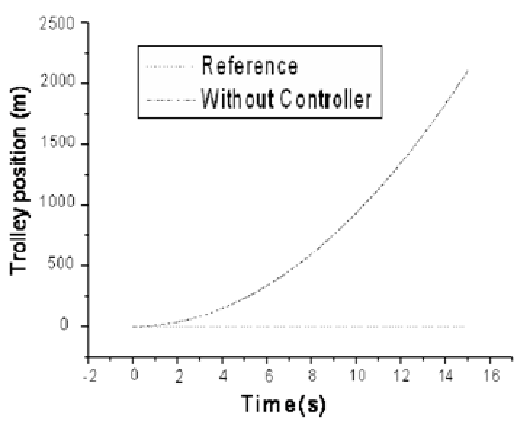


Figure 5. Simulated Plot for Trolley Position without Controller

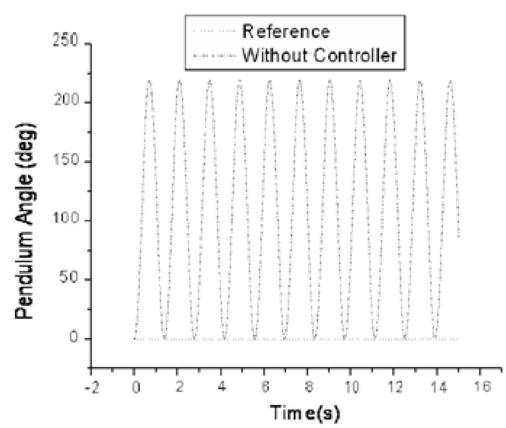


Figure 6. Simulated Plot for Pendulum Angle without Controller

The simulation results for the system void of any controller are shown in Figure 5 and 6 which is the behaviour of an unstable system. The first graph shows that the trolley positions were uncontrolled and could achieve an infinite position for the 0.4m input step response. Additionally, the pendulum swing angle becomes increasingly larger and uncontrolled. From the result, the 3DOF crane system could not perform as required.

6.2 System Performance with LQR Controller

Figure 7 shows the LQR controller simulink model for the gantry system. It was designed for controlling the position and swing angle. The system consists of setpoint block, jib control system block, jib model block, jib observer block, and the scopes block set. Setpoints block was used to generate step function and trolley setpoint slider. The trolley setpoint slider gain was used to initiate the required trolley position. Slider gain block will vary a scalar gain during the simulation. The range was set to ±0.4m for the max and min limit of the slider. Jib control system block consist of the LQR controller that will control the entire system of 3DOF crane. The gain block accepts real or complex scalar, vector or matrix data type supported by simulink. The gain needs to have a specific value in order to multiply the input and gain, which may be in a scalar, vector or matrix form. In our model, the gain was K_J(1:4) and the multiplication is Matrix (K*U) which means the input and gain are matrix multiplied with the input as the second operand. Gantry model was a plant for the 3DOF crane and consists of state-space and saturation block diagram. The state-space block will implement a system whose behaviour is defined by dynamic equation. The saturation block imposes upper and lower bounds of a signal. When the input signal is within the range specified by the lower and upper limit parameters, the input signal passes through unchanged. However, when the input signal is outer limits, the signal is clipped to the upper and lower bound. In this case, the limits were set up for ±7A because the current limit of DC motor that are used to move the trolley was ±7A. Observer was act as a filter to this system which filtered the noise and makes a signal smoother. The filtered was in high pass and low pass filter in the transfer function blocks that takes a scalar factor as an input signal. Finally, the visualizaton of the performance was done by the scope block. The scope displayed its input with respect to simulation time. In our system, the simulation time was set to 25 seconds. The results for LQR controller with 0.4m as a desired point are shown in the Figure 17 and 18.

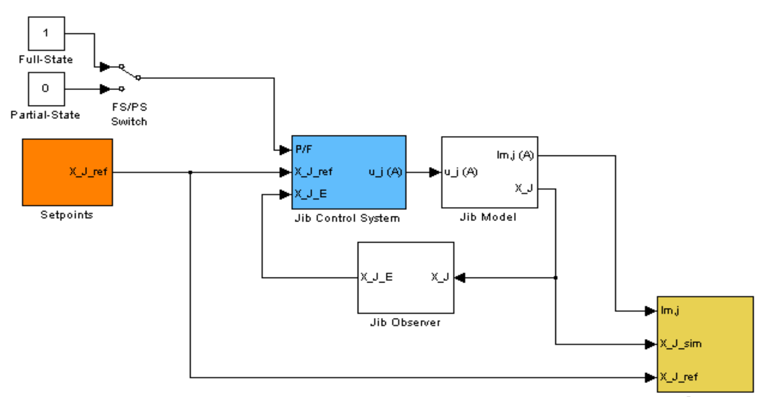


Figure 7. Jib System with LQR Controller

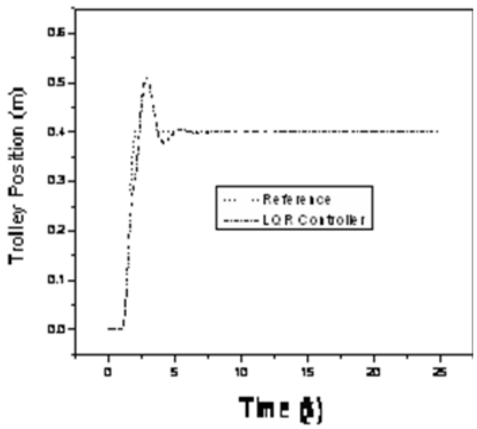


Figure 8. Trolley Position for LQR Simulated Result

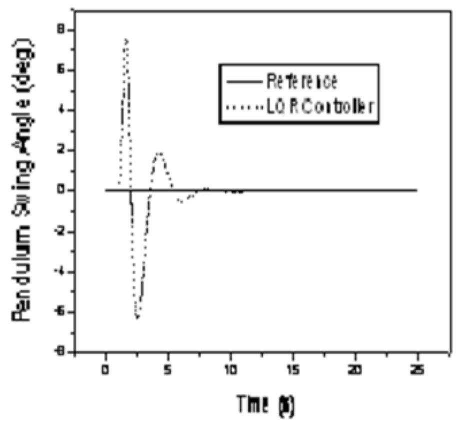


Figure 9. Pendulum Swing Angle for LQR Simulated Result

Table 3. Performance of LQR Controller for Position Control

Overshoot %	Rise Time (sec)	SettlingTime (sec)	Steady State Error
27.409%	0.974	4.711	0

Figure 8 shows the simulated result for positioning control and Table 3 is the performance of LQR control shown numerically. The result shows that 27.409% of overshoot, very fast rise time and settling time. This means that the trolley have injected with higher current and the motion is very fast, in controlling the trolley movement. At 4.711sec, the trolley's displacement was achieved to produce the desired position (at 0.4m) and with this condition, there will be no current supplied to the motor and hence the trolley comes to stationary.

Table 4. Performance of LQR Controller for Anti-swing Control

Maximum Amplitude (deg)	Minimum Amplitude (deg)	Settling Time (sec)
7.7745	-6.261	15.13

Figure 18 shows the simulated result for swing angle control and Table 4 is their performance of LQR controller. The result shows the maximum angle is about 7.7745 deg and the minimum angle is -6.261 deg. The pendulum stopped from swinging at 15.13 sec.

6.3 System Performance with Fuzzy Logic Controller

Figure 10 shows the FLC block diagram that was developed for the gantry system. FLC was used to control both, the positioning and the swing angle. It replaces LQR controller while other blocks were unchanged. There are two fuzzy logic controller blocks that were named as position_control to control the cart positioning process and the anti-swing_control for the anti swing controller. The fuzzy logic controller block implements fuzzy inference system. The inferences were created first and imported to these blocks.

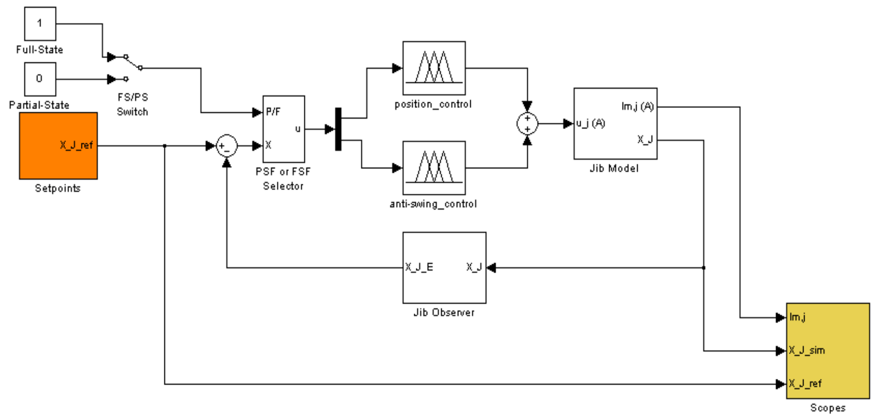


Figure 10. Gantry System with FLC

The simulation results for FLC are shown in Figure 11 and Table 6. It shows an overshoot of about 0.0244% and a shorter settling time. The trolley had been injected with suitable current in the range of ±7A and moves slowly in controlling the trolley movement. At 4.605sec, the trolley's movement had reached the desired position of 0.4m and stopped. Figure 12 shows the simulation result for swing angle controller and Table 6 is their performance. The result shows that the maximum angle is 0.8757 deg and the minimum angle is -0.5997 deg. The pendulum was stopped from swinging at time 14.29 sec.

Table 5. Performance of FLC for Position Control

Overshoot%	Rise Time (sec)	SettlingTime (sec)	Steady State Error
0.0244	3.205	4.605	0

Table 6. Performance of FLC for Pendulum Anti-swing Control

Maximum Amplitude (deg)	Minimum Amplitude (deg)	Settling Time (sec)
0.8757	-0.5997	14.29

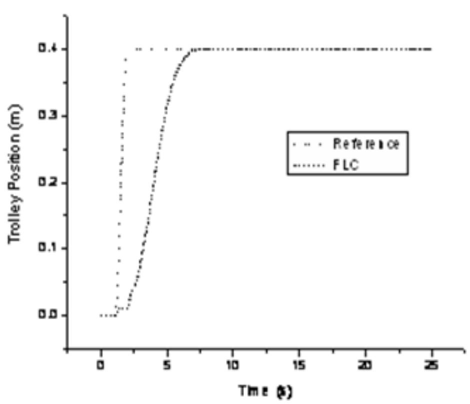


Figure 11. Trolley Position for FLC Simulated Result

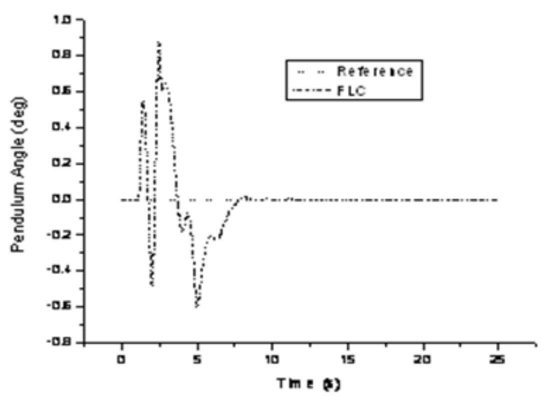
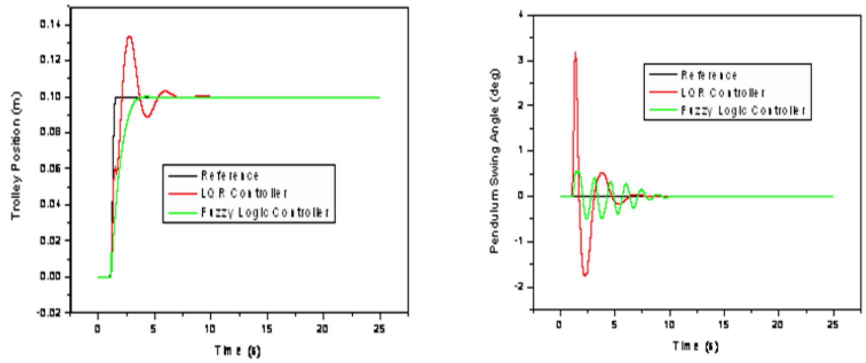


Figure 12. Pendulum Swing Angle for FLC Simulated Result

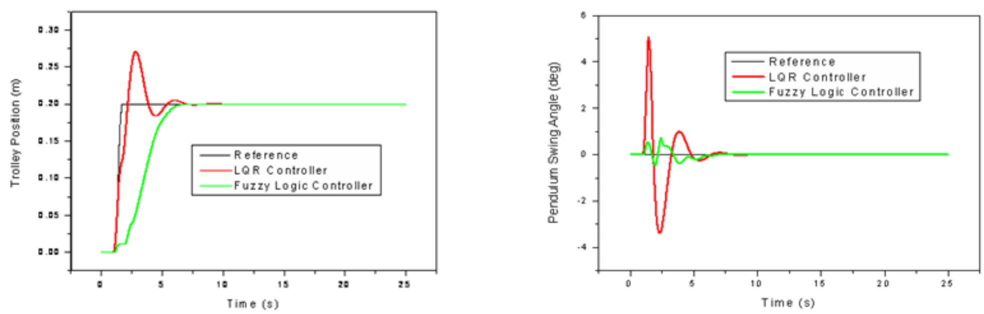
6.4 System Performance of LQR and FLC

In this section, performance comparison between LQR and FLC will be shown for different step input response.



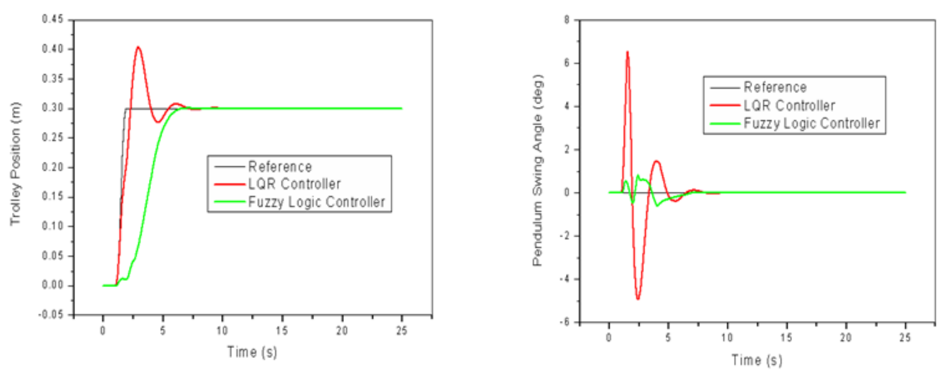
(a) Position response (b) Anti swing response

Figure 13. Response at 0.1m Step Input Reference



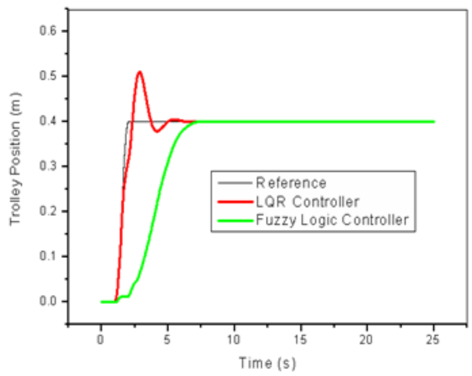
(a) Position response (b) Anti swing response

Figure 14. Response at 0.2m Step Input Reference

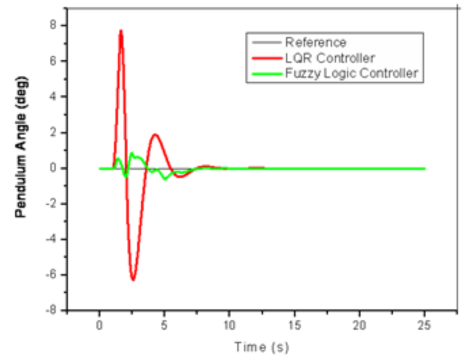


a) Position response b) Anti swing response

Figure 15. Response at 0.3m Step Input Reference



a) Position response



b) Anti Swing Response

Figure 16. Response to a 0.4m Step Input Reference

Table 7. Compared Performance of LQR and FLC for Position Control

TARGET POSITION (m)	CNTRL	PERFORMANCE			
		% OVERSHOOT	RISE TIME (s)	SETTLING TIME (s)	STEADY STATE ERROR
0.1	LQR	30.635	0.842	4.4390	0
	FLC	0.1	2.419	4.304	0
0.2	LQR	29.518	0.901	4.551	0
	FLC	-1.746	2.953	4.405	0
0.3	LQR	28.4464	0.943	4.637	0
	FLC	0.17	2.813	4.519	0
0.4	LQR	27.4087	0.974	4.711	0
	FLC	0.0244	3.205	4.605	0

Table 8. Compared Performance of LQR and FLC for Anti-swing Controller

TARGET POSITION (m)	CNTRL	AMP MAX (deg)	AMP MIN (deg)	SETTLING TIME (s)
0.1	LQR	3.1851	-1.7293	15.328
	FLC	0.5463	-0.496	13.122
0.2	LQR	5.0654	-3.3834	15.642
	FLC	0.5463	-0.3787	13.579

0.3	LQR	6.5067	-4.9274	15.804
	FLC	0.8121	-0.5989	14.175
0.4	LQR	7.7745	-6.261	15.13
	FLC	0.8757	-0.5997	14.29

The performances of FLC and LQR are compared via simulation. Various responses for .1m, 0.2m, 0.3m and 0.4m step input are shown in Figure 13, 14, 15 and 16. The details performances are shown in the Table 7 for position control while Table 8 shows the performances of anti-swing controller. The results showed that the FLC produced smaller overshoot as compared to LQR when 0.1m, 0.2m, 0.3m and 0.4m step input were used for position control. However, the rise times for FLC are slower than LQR controller but the settling time of FLC for all reference step input are faster than LQR controller. Meanwhile, their steady state errors for both controllers are negligible. Hence, the results showed that an overall performance of FLC is better than the conventional LQR controller. The performance of anti-swing controller shown in Table 8, confirmed that FLC is better in reducing the swing angle as compared to the LQR. The analysis is based on their swinging amplitude and settling time. For all step input references, LQR controller produced a large swing compared to FLC. Additionally, FLC produced better performance in settling time compared to the LQR controller.

7. Conclusions

In this paper, we proposed a FLC to control a 3-DOF crane system and tested by simulation using MATLAB. The performance of FLC was analyzed and compared to conventional LQR controller. The simulation results showed that the proposed FLC produced better performance compared to the conventional LQR. Additionally, FLC has simpler design method, algorithm and avoided extensive mathematical analysis. As a conclusion, the objectives to propose a better control strategy for the transfer of load and suppress the swing angle for 3DOF crane system were successfully done. The FLC design is simpler and easy to implement. Some of the recommendations for future works are as follows: FLC can be tuned more appropriately based on the designing to have a better performance for positioning and swing control; FLC can be design using other types of membership function such as Gaussian, trapezoidal and many more to see the different effect of tuning using these types of membership function; FLC could be applied to other types of control system since this controller is easy and have a simpler design.

References

[1] C. Li, C. Y. Lee, "Fuzzy motion control of an auto-warehousing crane system", IEEE Trans Ind Electron, vol. 48, no. 5, **(2001)**, pp. 983–94.

[2] Y. C. Liang and K. K. Koh, "Concise anti-swing approach for fuzzy crane control", IEE Electron Lett., vol. 3, no. 2, **(1997)**, pp. 167–168.

[3] C. Y. Chang CY, Adaptive Fuzzy Controller of the Overhead Cranes with Nonlinear Disturbance. IEEE Trans Ind Inform, vol. 3, no. 2, **(2007)**, pp. 164–172.

[4] H. H Lee and S. K. Cho, "A New Fuzzy-Logic Anti-Swing Control for Industrial Three-Dimensional Overhead Cranes," in Proc. Int. Conference on Robotics & Automation 2001, Seoul, Korea, **(2001)** May 21-26, pp.2956-2961.
[5] D. M. Dawson, Y. Fang, W. E. Dixon and E. Zergeroglu, "Nonlinear Coupling Control Laws For a 3-DOF Overhead Crane System," *Proc. IEEE Conf. on Decision and Control*, **(2001)**, pp. 3766-3771.
[6] H. M. Omar, "Control of Gantry and Tower Crane" , Blacksburg, Virginia, **(2003)**.
[7] J. Jalani, "Control Strategies for Automatic Gantry Crane System," International Islamic University of Malaysia, **(2005)**.
[8] M. Z. Othman, "A New Approach for Controlling Overhead Travelling Crane Using Rough Controller," *Int. Journal of Intelligent Technology*, vol. 1, no. 3, **(2006)**, pp. 240-242.
[9] D. S. Naidu, "Optimal Control Systems" Idaho, USA, CRC Press, **(2003)**, pp. 101-104.
[10] Z. X. Cai, "Intelligent Control: Principles, Techniques and Applications." vol. 7, River Edge, N.J: World Scientific, **(1997)**, pp. 182-238.
[11] T. J. Ross, "Fuzzy Logic with Engineering Application", 2nd. ed. West Sussex: England, **(2004)**, pp. 151-165.
[12] K. M. Passino and S. Yurkovich, Fuzzy Control, Addison Wesley Longman, 1998.
[13] C. C. Cheng and C. Y. Chen , "Controller Design for an Overhead Crane System with Uncertainty", Journal of Control Eng. Practice, vol. 4, no. 5, **(1996)**, pp. 645-653.
[14] A. A. Al-Mousa, "Control of Rotary Cranes Using Fuzzy Logic and Time-Delayed Position Feedback Control", Virginia Tech., Blacksburg, VA, **(2000)**.
[15] Szpytko and J. Smoczek, "Adaptation Control Technique of Overhead Crane Systems," *Int. Journal*, **(2003)**.
[16] A. Benhidjeb and G. L. Gissinger, "Fuzzy Control of an Overhead Crane Performance Comparison With Classic Control," Journal of Control Eng. Practice, vol. 3, no. 12, **(1995)**, pp. 1687-1696.
[17] Fuzzy Toolbox User's Guide, The MathWorks Inc., **(2001)**.

Nomenclature

Symbol	Description
g	Gravitational acceleration constant
J_{ψ}	Jib motor equivalent moment of inertia
$K_{g,j}$	Motor gear ratio for jib
$K_{t,j}$	Jib motor torque constant
l_p	Vertical distance of payload from jib arm
m_p	Mass of payload
$m_{trolley}$	Mass of trolley
$\eta_{g,j}$	Jib motor gearbox efficiency
$\eta_{m,j}$	Jib motor efficiency
$r_{j,pulley}$	Radius of trolley pulley from pivot to end of tooth
A	State matrix

B	Input matrix
C	Output matrix
D	Direct transmission

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