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Modelling and Fuzzy Logic Control of an Underactuated Tower Crane System

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Abstract: Tower crane is one of the flexible maneuvering systems that has been applied pervasively as a powerful big-scale construction machine. The under-actuated tower crane system has nonlinearity behavior with a coupling between translational and slew motions which increases the crane control challenge. In practical applications, most of the tower cranes are operated by a human operator which lead to unsatisfactory control tasks. Motivated to overcome the issues, this paper proposes a fuzzy logic controller based on single input rule modules dynamically connected fuzzy inference system for slew/translational positioning and swing suppressions of a 3 degree-of-freedom tower crane system. The proposed method can reduce the number of rules significantly, resulting in a simpler controller design. The proposed method achieves higher suppressions of at least 56% and 81% in the overall in-plane and out-plane swing responses, respectively as compared to PSO based PID+PD control.

Keywords: Crane systems; Flexible system; Fuzzy logic control; Intelligent control; Single input rule module.

1. INTRODUCTION

In decades, cranes have been utilized pervasively and play a dominant role in transporting heavy loads in construction sites, factories, harbor and marine. Typically, cranes are prone to an excessive payload swing due to incompetent of crane operator to handle the crane operation [1]. When a severe swing occurs, the operation might be delayed until the payload is stable. One of the cranes that has been extensively applied is a tower crane system as a powerful transportation machine used in various construction sites. Control of the tower crane system has been proposed which include an adaptive control [2], command shaping [3-4], neural network [5], gain scheduling control [6] and model predictive control [7]. On the other hand, a Fuzzy Logic Control (FLC) has also been widely applied for vibration control in various systems [8-12]. An FLC has a strong adaptability and it does not require an accurate model of the controlled object due to its intelligent method [13]. Commonly, existing control techniques for a complex system are designed based on linearized system dynamics, and most of them require an exact model knowledge [2]. In contrast, an FLC has a benefit which replaces the role of a mathematical model with a fuzzy model, based on the rules constructed in an if-then format. Diverse designs of an FLC controllers in tower crane systems have been proposed [8-10,14-15].

Generally, when using a conventional IF-THEN fuzzy inference method [16], an antecedent part of each fuzzy rule is constructed using all or majority of the input items of the system, and this makes the number of rules increases exponentially. A rule explosion can lead to an overlap problem and may result in a computational burden [17]. This type of inference method is inconvenient to be implemented especially for a complex system such as tower crane due to the utilization of many inputs which could lead to the difficulties in constructing and defining all the fuzzy rules simultaneously. In order to overcome this problem, a Single Input Rule Modules Fuzzy Logic Control (SIRMs-FLC) was proposed [18-22] to effectively reduce the number of fuzzy rules as compared to the conventional method. In this technique, its antecedent part has only one input item per rule, so that the number of rules applied in the design is optimally reduced.

SIRMs-FLC has also been proposed for an overhead crane utilizing a single-pendulum [23] and double-pendulum [24-25]. However, control of a tower crane system using SIRMs-FLC has not been reported in the literature. It is worthwhile to point out that the crane control challenge increases due to the complex nonlinear dynamic of tower crane. In order to achieve an efficient swing/position control of the tower crane, the following issues must be considered:

1) Unlike an overhead crane [26] that behaves linearly, the tower crane inherently has nonlinearity behavior. The effects of nonlinearities are more substantial for the tower crane that deals with a slew motion.
2) Furthermore, a payload tends to swing in two directions that are longitudinal and lateral swings, resulted from both the

cart's translation and jib's slew motions respectively. The longitudinal swing angle can be possibly suppressed by controlling the cart's motion, but control of the lateral swing direction may need a proper and effective control strategy. It is desirable to design a control scheme that can suppress the load swing in both directions concurrently.

3) Most of existing controllers are designed based on a linearized dynamic model in which the nonlinear terms are neglected. For example, the payload swing of the crane is assumed to be small which could affect the controller performances when the crane is subjected to a large swing due to simultaneous cart and jib motions, time-varying parameter (payload hoisting) or disturbances.

Motivated to overcome this issue, this paper proposes the SIRMs-FLC for tower crane to achieve an efficient control of a simultaneous slew and translation position, together with the reduction of payload swings resulted from the simultaneous motions. Besides, the designed SIRM was also connected with an importance degree so that all the control components can be realized in parallel. To the best of authors' knowledge, the proposed SIRMs-FLC is the first approach applied to the tower crane system. In this work, simulations are carried out to evaluate the performances of the proposed SIRMs-FLC. A PID+PD controller is also implemented for performance comparison. The proposed controller can achieve an efficient control of a simultaneous slew and translation position, together with a significant payload swing suppression under the simultaneous cart and jib motion than the comparative method.

2. MODELLING OF A TOWER CRANE

A tower crane consists of a cart/trolley that moves the load along the jib in a translational direction. The crane has a slew motion that rotates the jib about a fixed vertical axis which is normally up to 180 or 360 degrees. Normally, the tower crane is located at a fixed place [5], repeating similar processes, especially on a construction site.

Figure 1 illustrates a model of tower crane system. The origin of the xyz plane is located at the point where the jib and tower meet. The z-axis is located along the tower upwards while x-axis is along the horizontal jib. The jib rotates and produces an angle γ. A distance r indicates a path taken by the trolley as it moves from the origin of xyz plane up to the suspension point of the cable on the trolley. L denotes the cable length and m denotes the payload mass. Payload swing angles comprise of in-plane angle ϕ and out-plane angle θ. The load is modeled as a point mass. Besides, the relationship between the load dynamics and the crane dynamics is negligible because the crane mass is assumed to be very large as compared to that of the load.

The equations of motions are derived by using the Lagrangian's approach. Based on Figure 1, the load and trolley position vectors can be written as:

$$\vec{R}_L = \{r - L\cos\theta\sin\phi\,, L\sin\theta\,, -L\cos\theta\cos\phi\} \tag{1}$$

$$\vec{R}_T = \{r, 0,0\} \tag{2}$$

The velocities of the trolley and the load are given as:

$$\vec{\dot{R}} = \frac{\mathrm{d}\vec{R}}{\mathrm{d}t} + \vec{\omega} \times \vec{R} \tag{3}$$

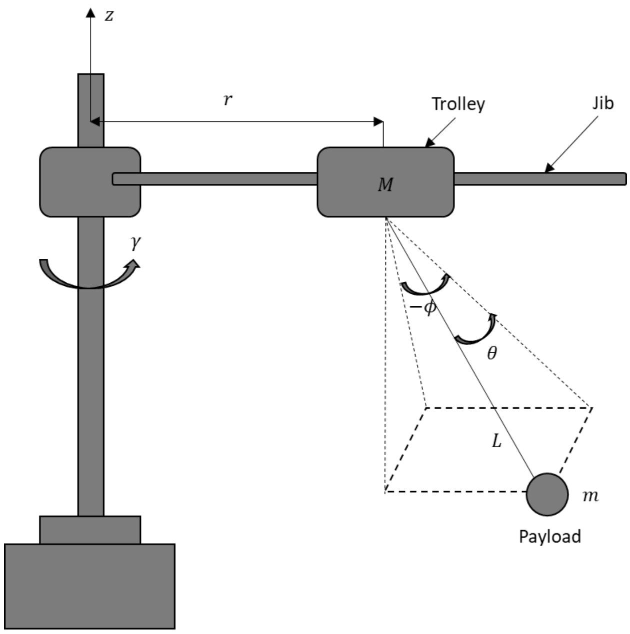

Figure 1. Tower crane system

where $\vec{\omega} = \{0,0,\dot{\gamma}\}$ is the angular velocity of the tower. The kinetic and potential energies and the dissipation function are given by:

$$PE = \frac{1}{2}m\vec{\dot{R}}_L.\vec{\dot{R}}_L + \frac{1}{2}M\vec{\dot{R}}_T.\vec{\dot{R}}_T + \frac{1}{2}J_o\dot{\gamma}^2 \tag{4}$$

$$KE = -mgL\cos\theta\cos\phi \tag{5}$$

$$D = \frac{1}{2}b_r\dot{r}^2 + \frac{1}{2}b_\gamma\dot{\gamma}^2 \tag{6}$$

where J_o is the moment of inertia of the jib about the z-axis, and b_r and b_γ are the friction coefficients for the trolley and the tower, respectively. The generalized forces corresponding to the generalized displacement $\vec{q} = \{r,\phi,\gamma,\theta\}$ are:

$$\vec{F} = \{F_x, 0, F_\gamma, 0\} \tag{7}$$

Constructing the Euler Lagrange equation $\mathcal{L} = PE - KE$,

$$\frac{d}{dt}\left(\frac{\partial\mathcal{L}}{\partial\dot{q}_j}\right) - \frac{\partial\mathcal{L}}{\partial q_j} = F_j \tag{8}$$

Hence, the equations of motion are given as:

$$\begin{aligned}&(m+M)\ddot{r} + b_r\dot{r} + mL\cos\theta\sin\phi\,\dot{\gamma}^2 - (m+M)r\dot{\gamma}^2 - 2mL\cos\theta\,\dot{\gamma}\dot{\theta} + mL\cos\theta\sin\phi\dot{\theta}^2 + \\ &2mL\cos\phi\sin\theta\dot{\theta}\,\dot{\phi} + mL\cos\theta\sin\phi\,\dot{\phi}^2 - 2mL\big(\sin\theta\,\dot{\gamma} - \sin\theta\sin\phi\,\dot{\theta} + \cos\theta\cos\phi\dot{\phi}\big) - \\ &m\cos\theta\sin\phi\ddot{L} - mL\sin\theta\ddot{\gamma} + mL\sin\theta\sin\phi\ddot{\theta} - mL\cos\theta\cos\phi\,\ddot{\phi} = F_r\end{aligned} \tag{9}$$

$$\begin{aligned}&L\cos\theta^2\ddot{\phi} + \cos\theta\left(g\sin\phi - L\cos\theta\cos\phi\sin\phi\dot{\gamma}^2 + \cos\phi\,r\dot{\gamma}^2 + 2L\cos\theta\cos\phi\dot{\gamma}\dot{\theta} - 2L\sin\theta\dot{\theta}\dot{\phi} + \right. \\ &\left. 2\dot{L}\big(\cos\phi\sin\theta\,\dot{\gamma} + \cos\theta\dot{\phi}\big)\right) - \cos\theta\cos\phi\ddot{r} + L\cos\theta\cos\phi\sin\theta\ddot{\gamma} = 0\end{aligned} \tag{10}$$

$$\begin{aligned}&(J_o + mL^2\sin\theta^2 + m\cos\theta^2L^2\sin\phi^2 - 2m\cos\theta\,L\sin\phi r + mr^2 + Mr^2)\ddot{\gamma} + 2m\cos\theta\,r\dot{L}\dot{\theta} - \\ &mL\sin\theta r\dot{\theta}^2 - 2m\cos\phi L^2\sin\theta^2\dot{\theta}\dot{\phi} - m\cos\theta\,L^2\sin\theta\sin\phi\,\dot{\phi}^2 - mL\dot{L}\big(2\sin\phi\dot{\theta} - \\ &\cos\phi\sin2\theta\,\dot{\phi}\big)\dot{\gamma}\Big(b_\gamma + r\big(-2m\cos\theta\sin\phi\,\dot{L} + 2(m+M)\dot{r}\big) + mL^2\big(\cos\phi^2\sin2\theta\,\dot{\theta} + \\ &\cos\theta^2\sin2\theta\,\dot{\phi}\big) + 2mL\Big(\big(\sin\theta^2 + \cos\theta^2\sin\phi^2\big)\dot{L} - \cos\theta\sin\phi\,\dot{r} + \sin\theta\sin\phi\,r\dot{\theta} - \cos\theta\cos\phi\,r\dot{\phi}\Big)\Big) + \\ &m\sin\theta\,r\ddot{L} - mL\sin\theta\,\ddot{r} + (-(m\cos\theta^2L^2\sin\phi) - mL^2\sin\theta^2\sin\phi + m\cos\theta\,Lr)\ddot{\theta} + \\ &m\cos\theta\cos\phi L^2\sin\theta\,\ddot{\phi} + b_r\dot{\gamma} = F_\gamma\end{aligned} \tag{11}$$

$$\begin{aligned}&L\ddot{\theta} + g\cos\phi\sin\theta + 2\cos\theta\dot{r}\dot{\gamma} - \tfrac{1}{4}L\sin2\theta\,\dot{\gamma}^2 - \tfrac{1}{4}L\cos\phi^2\sin2\theta\,\dot{\gamma}^2 + \tfrac{1}{4}L\sin2\theta\sin\phi^2\dot{\gamma}^2 - \\ &r\sin\theta\sin\phi\,\dot{\gamma}^2 + \dot{L}\big(-2\sin\phi\,\dot{\gamma} + 2\dot{\theta}\big) - L\cos\phi\dot{\gamma}\dot{\phi} + L\cos\theta^2\cos\phi\,\dot{\gamma}\dot{\phi} + L\cos\phi\sin\theta^2\dot{\gamma}\dot{\phi} + \\ &L\cos\theta\sin\theta\,\dot{\phi}^2 + \sin\theta\sin\phi\ddot{r} + (-L\sin\phi + r\cos\theta)\ddot{\gamma} = 0\end{aligned} \tag{12}$$

3. CONTROLLER DESIGN

This section discusses the theoretical and design of SIRMs-FLC for translation and slew positioning concurrently, together with payload swing reductions of the tower crane system. The benefit offered by the SIRMs model is that each of the SIRMs is dynamically weighted according to the priority in such a way that all the control components can be realized in parallel. The dynamic weights will keep on changing significantly to adapt according to the control situation.

There are three components that need to be controlled which include trolley/cart position, jib slew angle, in-plane payload swing angle and out-plane payload swing angle. Figure 2 shows the block diagram of the SIRMs-FLC design. The antecedent

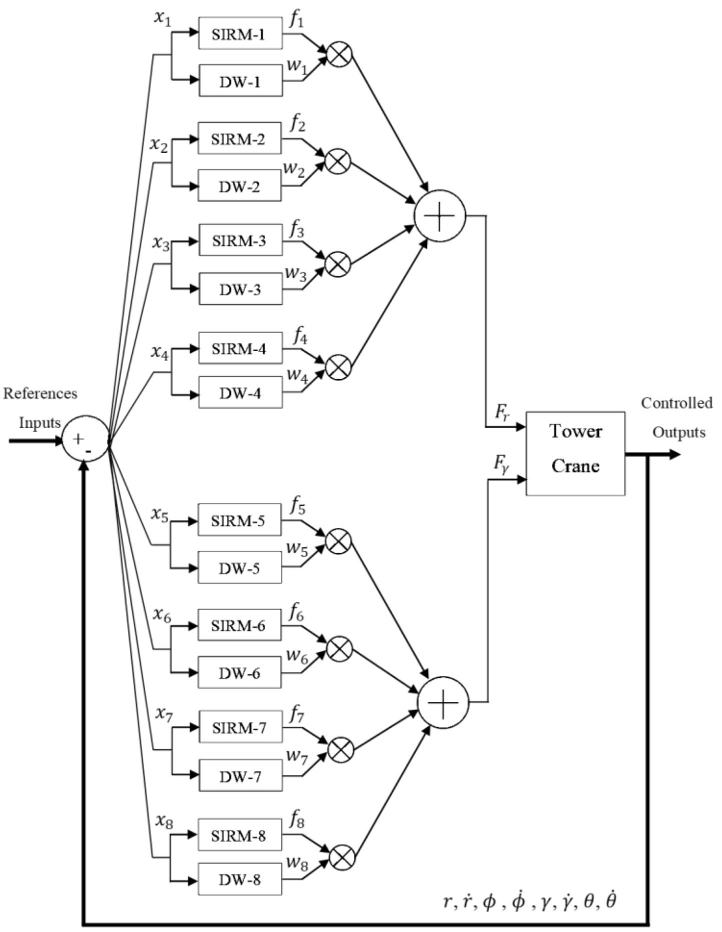

Figure 2. Block diagram of SIRM-FLC

variables/input items $x_i (i = 1, 2, \ldots, 8)$ are assigned with trolley position r, trolley velocity $\dot{r}$, in-plane angle ϕ, in-plane angular velocity $\dot{\phi}$, jib slew angle γ, jib angular velocity $\dot{\gamma}$, out-plane angle θ and out-plane angular velocity $\dot{\theta}$ respectively. Each of the input item is sent to its corresponding SIRM-i block, while the absolute value of each input item is sent to its own dynamic weight block, DW-i. The SIRM-i is given as:

$$\text{SIRM} - i\text{:} \left\{ R_i^j : \text{if } x_i = A_i^j \text{ } then \text{ } f_i = C_i^j \right\}_{j=1}^{m_i} \tag{13}$$

where $i = 1, 2, \ldots, n$ is the index number of SIRMs and $j = 1, 2, \ldots, m_i$ is the index number of the rules in the SIRM-i. SIRM-i represents the SIRM of the ith input item and R_i^j denotes the jth rule in the SIRM-i. The antecedent part of the SIRM model is given as ith input item x_i which is the only variable in the antecedent part and f_i is a consequent variable. The jth rule of the SIRM-i consists of A_i^j that indicates a fuzzy subset of x_i and C_i^j indicating a fuzzy subset of a singleton real number of f_i.

To distinguish the role or importance degree of each input item based on the system performance, a dynamic weight d_i is used independently for each input item x_i, which is given as:

$$w_i = k_i + B_i \Delta d_i \tag{14}$$

k_i and B_i are the base value and breadth respectively which are the predefined control parameters to ensure a minimum weight that suitable for the corresponding input item. Δd_i is the dynamic variable that is determined by the fuzzy rules so that it will have an online adaptation to adjust its role according to the control/system performances. The dynamic weight w_i guarantees that the controller can realize all the control components in parallel by dynamically weighted each of the SIRM models according to their priority orders. The fuzzy inference result of the consequent variable is computed as:

$$f_i = \frac{\sum_{j=1}^{m_i} A_i^j(x_i) C_i^j}{\sum_{j=1}^{m_i} A_i^j(x_i)} \tag{15}$$

Despite the complex mathematical plant model, the FLC only requires inputs to be applied to derive the proper driving force or the control signals of the tower and jib motors $F = [F_r \;\; F_\gamma]^T$ of the crane. The driving force for the translation positioning is given as:

$$F_t = \sum_{i=1}^{4} w_i f_i \tag{16}$$

whereas, the driving force for slew positioning is determined as:

$$F_s = \sum_{i=5}^{8} w_i f_i \tag{17}$$

Considering the priority to be accomplished by the control components based on the control situation with dynamically weighted, these control signals will drive the tower crane system to achieve a desired slew/translation positioning, together with the suppression of in-plane and out-plane swing angles effectively. The SIRMs design is performed as fuzzy inference models that constructed by fuzzy rules. The SIRMs design considers the trolley and slew motions concurrently, together with the in-plane and out-plane swing angles suppression. The detailed settings of the SIRMs and dynamic weights for the trolley positioning, jib positioning, and payload angles are discussed in the next section.

3.1 Positioning Control and Swing Suppression

SIRM-1, SIRM-2, SIRM-5, and SIRM-6 are used for the position control. For a rapid load transportation, the trolley position error e_r and the slew angle error e_γ are considered to decide whether the controller should accelerate or decelerate the trolley and jib respectively. It also gives the direction of the target position. Meanwhile, SIRM-3 and SIRM-4, SIRM-7 and SIRM-8 are used for the anti-swing control of in-plane swing angle ϕ and out-plane swing angle θ respectively. Table 1 shows the implementation of SIRMs applied for a simultaneous slew and translation position and swing suppression.

3.2 Dynamic Weights

Initially, when the trolley is far away from the destination and the other state variables are nearly zero, the dynamic weight of e_r should be increased so that the contribution of the control action that has been set up in SIRM model for e_r is emphasized as a main part of the output item. Hence, the trolley will be driven toward the destination. The same control mechanism utilized for the e_γ in which when the destination is far, its corresponding dynamic weight will be high to force the jib to rotate toward the target. The dynamic weight varies depending on the current position until it reaches the destination. Table 2 shows the implementation of dynamic weights applied for a simultaneous slew and translation position and swing suppression.

The role of dynamic weight plays a significant contribution in SIRM because by adjusting its weight, all the output of the SIRMs can be realized in parallel and each of the output can be emphasized in an online manner based on the situation of the payload and trolley. Consequently, the slew and translational positioning control can be achieved precisely, together with the swing angles suppression.

Table 1: Position control and swing suppression using SIRM-FLC

	Input	Value	Force	Result
Position control	e_r and e_γ	Positive	Positive	Trolley and jib tend to reach the destination
		Negative	Negative	
	$\dot{r}$ and $\dot{\gamma}$	Positive	Negative	ϕ and θ will be small
		Negative	Positive	
Swing suppression	ϕ and θ	Positive	Positive control force is needed to ensure that the payload rotates clockwise	ϕ and θ tend to suppress expressively
		Negative	Negative control force is needed to ensure that the payload rotates anti-clockwise	
	$\dot{\phi}$ and $\dot{\theta}$	Positive	Positive	$\dot{\phi}$ and $\dot{\theta}$ will reduce significantly
		Negative	Negative	

Three triangular membership functions namely negative big (NB), zero (ZO) and positive big (PB) are defined for the SIRMs. On the other hand, three triangular membership functions namely small (S), medium (M) and big (B) are defined for the dynamic weights. Tables 3-5 describe the fuzzy rules for position control, swing suppression and dynamic weight respectively.

Table 2. Dynamic weights using SIRM-FLC

Input	Dynamic weight	Result
Trolley is far away from the destination	Dynamic weight of e_r should be increased	Trolley and jib tend to reach the destination
Jib is far away from the destination	Dynamic weight of e_r should be increased	
Trolley velocity, $\dot{r}$ is high	Dynamic weight of $\dot{r}$ will be strengthened	Trolley and jib will then be moved slowly to ensure that no severe payload swing angles throughout the trajectory
Jib angular velocity, $\dot{\gamma}$ is high	Dynamic weight of $\dot{\gamma}$ will be strengthened	
In-plane swing angle, ϕ is big	Dynamic weight of ϕ will increase	To ensure that the contribution of control action toward reducing the ϕ and θ are prioritized over the others
Out-plane swing angle, θ is big	Dynamic weight of the θ will increase	
In-plane angular velocity, $\dot{\phi}$ is large	Dynamic weight of $\dot{\phi}$ will increase	$\dot{\phi}$ and $\dot{\theta}$ will reduce significantly
Out-plane angular velocity, $\dot{\theta}$ is large	Dynamic weight of $\dot{\theta}$ will increase	

Table 3. Fuzzy rules in the SIRMs for position control

Antecedent variable x_i $(i = 1, 2, 5, 6)$	Consequent variable f_i $(i = 1, 5)$	Consequent variable f_i $(i = 2, 6)$
NB	-1.0	1.0
ZO	0.0	0.0
PB	1.0	-1.0

Table 4. Fuzzy rules in the SIRMs for swing suppression

Antecedent variable x_i $(i = 3, 4, 7, 8)$	Consequent variable x_i $(i = 3, 4, 7, 8)$
NB	-1.0
ZO	0.0
PB	1.0

Table 5. Fuzzy rules of the dynamic weight

Antecedent variable $\lvert x_i \rvert$	Consequent variable Δw_i
S	0.0
M	0.5
B	1.0

4. RESULTS AND DISCUSSIONS

To verify the crane performance, the results are obtained through simulation work using the Matlab software. These results are significant in investigating the performance of the SIRM fuzzy logic controller for the position control that involves trolley and jib slew motions simultaneously, together with swing suppression. Table 6 presents the system parameters for the tower crane system.

Since both trolley and jib move simultaneously, these motions create two payload swing angles that need to be controlled at the same time. The initial jib slew and trolley translation positions are set as $\gamma(0) = 0^{\circ}$ and $r(0) = 0$ m respectively, while the target of jib slew and trolley translation positions are set as $\gamma_d = {}^{\pi}/_{2}$ rad and $r_d = 0.4$ m respectively. As comparison, proportional integral derivative plus proportional derivative (PID+PD) controller was utilized [27] as shown in Figure 3. The optimal gains, K_p, K_i, K_d, K_{ps} and K_{ds} of PID+PD were tuned by using a Particle Swarm Optimization (PSO) as shown in Table 7.

Table 6. System parameters

System parameters	Values
Cable length, L	0.6 m
Gravitational constant, g	9.8 ms^{-2}
Viscous damping, b_r, b_γ	100, 75 Ns/m
Mass of payloads, m	800 g
Mass of trolley, M	1.155 kg

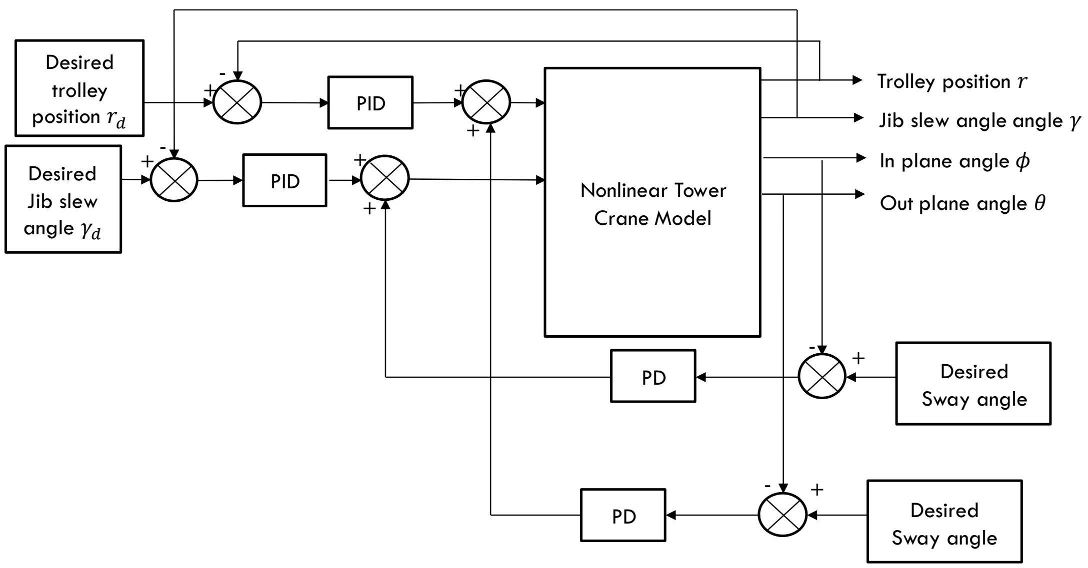

Figure 3. PID+PD controller block diagram

Figure 4 shows the relationship between the iteration and objective function where PSO managed to converge in solving a minimization problem based on the index absolute error for comparative method. When implementing the PID+PD and SIRMs-FLC controllers, the position control of SIRMs-FLC shown superior results in terms of transient and steady-state performances over the PID+PD. Figure 5 and Figure 6 illustrate the position controls of translation and slew respectively. The SIRMs-FLC managed to arrive at the target within 5 s for both translation and slew positions while PID+PD has shown unsatisfactory results with some overshoots. This verifies that the SIRMs-FLC can effectively prevent the trolley and jib motions from reaching beyond the set point (i.e., eliminating overshoots) which is desirable for practical application to avoid from hitting obstacles around the working space.

Table 7. PID+PD gains tuned by PSO

	Position control (PID)		
	K_p	K_i	K_d
Translation positioning, r	20	0.1	0.01
Slew positioning, γ	13.7	10	0.1
	Swing control (PD)		
	K_{ps}	K_{ds}	
In-plane swing angle, ϕ	3	1	
Out-plane swing angle, θ	2	2	

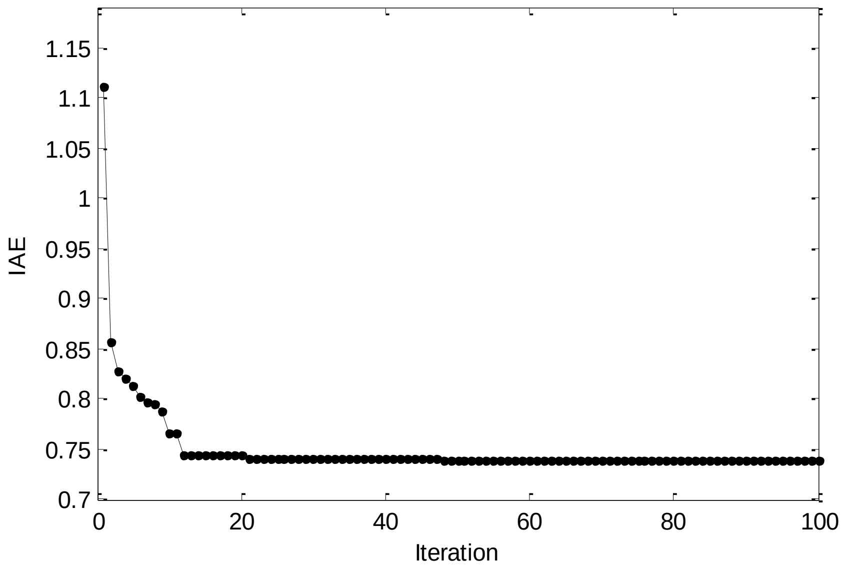

Figure 4. Relationship between iteration and IAE

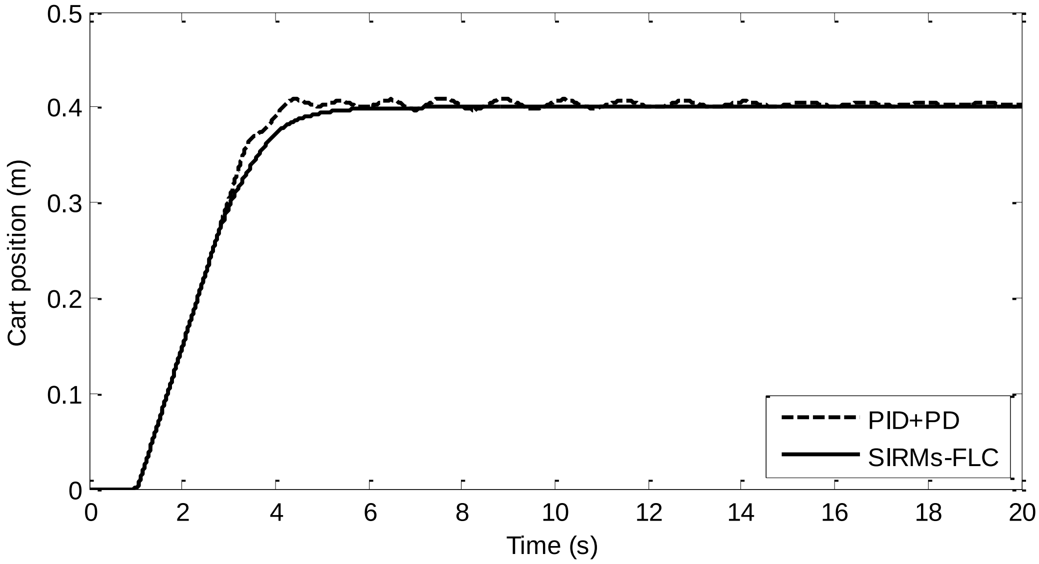

Figure 5. Translation control of the SIRMs-FLC and PID+PD methods

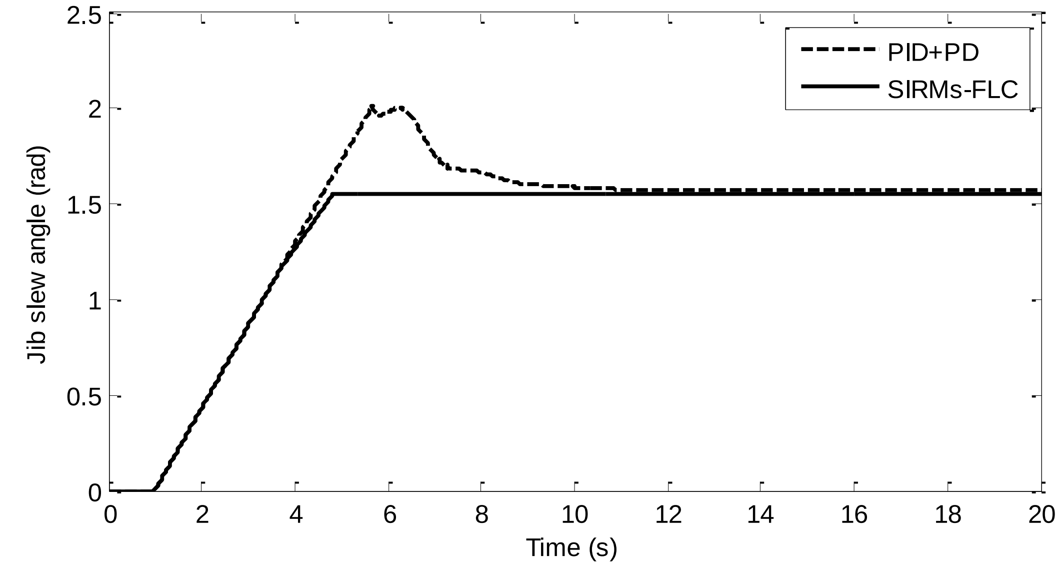

Figure 6: Jib slew angle of the SIRMs-FLC and PID+PD methods

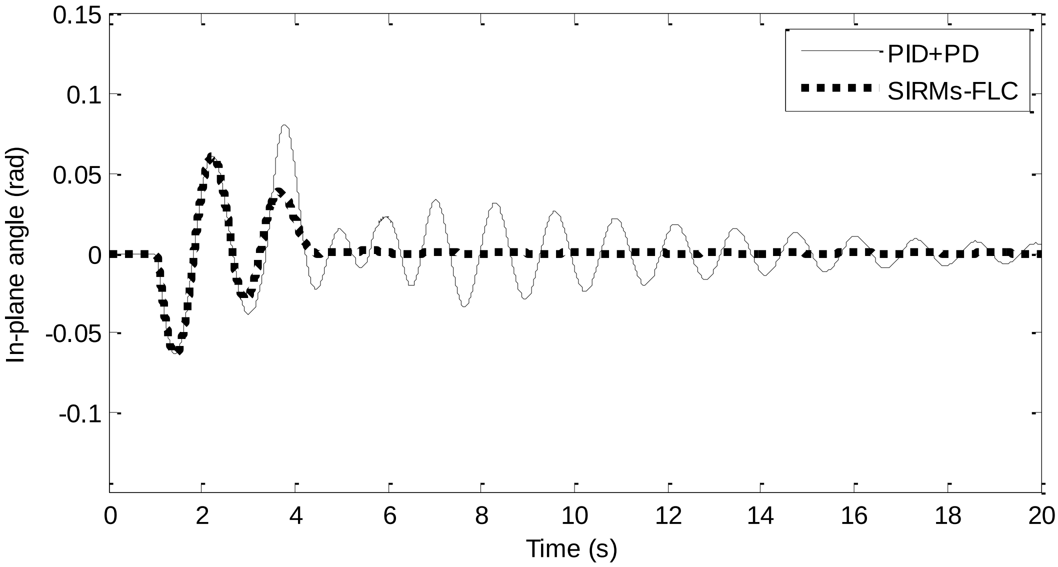

Figure 7. In-plane angle of the SIRMs-FLC and PID+PD methods

By comparing the swing suppression results, there are two swing angles to be considered which are in-plane ϕ and out-plane θ angles. In terms of ϕ, the SIRMs-FLC presented a better suppression as compared to the PID+PD since the maximum swing angle amplitude of SIRMs-FLC is approximately 0.06 rad which is lower than the PID+PD (0.08 rad) (see Figure 7). Besides, it was also observed that the SIRM-FLC has shown no residual swing as compared to PID+PD. It is important that the swing angle is suppressed significantly without any residual swing to save the operation time and increase the productivity.

Tower crane slewing and translation movements will excite oscillations in both the radial and tangential directions that correspond to the in-plane and out-plane angles respectively. Figure 8 illustrates the swing suppression of the out-plane angle θ using both approaches. The maximum swing angles amplitude of SIRMs-FLC is 0.058 rad which is lower as compared to the PID+PD (0.15 rad). Both methods have shown no residual swing but SIRMs-FLC has achieved a faster swing suppression as compared to PID+PD.

Owing to the objective of the crane control, the trolley and jib should reach the destination as fast as possible while able to reduce and eliminate the payload angle. The PID+PD method has shown its capability in reducing the swing angles, but it was unable to control the translation and slew positioning well. It provides an indication of the difficulty of the PID+PD controller in satisfying the objectives of the crane control. As for the SIRMs-FLC, both position and swing suppression are in a good control since it managed to obtain a trade-off or a balance control between both of it. Hence, from the above analysis, it is evident that the proposed controller is effective for controlling the tower crane system and produced satisfactory results.

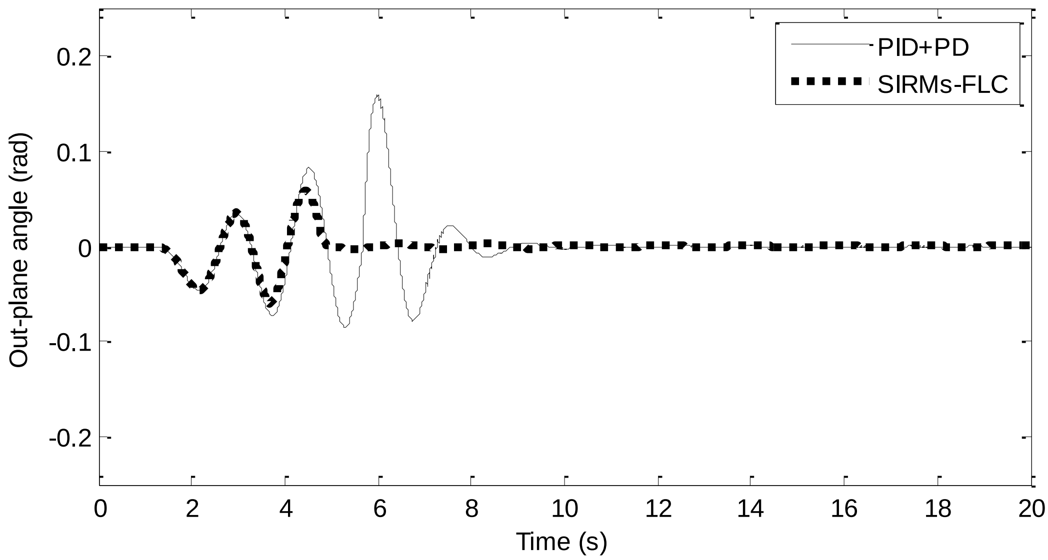

Figure 8. Out-plane angle of the SIRMs-FLC and PID+PD methods

5. CONCLUSION

The SIRMs fuzzy logic controller was designed and utilized for position control and swing suppression of a tower crane system. Simulation results showed that the SIRMs-FLC recorded higher suppressions in maximum and residual payload sway responses. Besides, the proposed controller can be easily designed without a prior knowledge of the tower crane's nonlinear dynamical equation as required by other conventional control strategies. For future work, an improved SIRMs can be designed which is robust to wind disturbance and can adapt to uncertainties. These factors are crucial to be considered as they always poorly degrade the crane performances in a real application.

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