SINGLE INPUT FUZZY CONTROLLER WITH COMMAND SHAPING SCHEMES FOR DOUBLE-PENDULUM-TYPE OVERHEAD CRANE

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Abstract
This paper presents investigations into the development of composite control schemes for trajectory tracking and anti-sway control of a double-pendulum-type overhead crane (DPTOC) system. A nonlinear DPTOC system is considered and the dynamic model of the system is derived using the Euler-Lagrange formulation. The proposed method, known as the Single Input Fuzzy Logic Controller (SIFLC), reduces the conventional two-input FLC (CFLC) to a single input single output (SISO) controller. The SIFLC is developed for position control of cart movement. This is then extended to incorporate input shaping schemes for anti-swaying control of the system. The input shapers with different mode selection are designed based on the properties of the system. The results of the response with the controllers are presented in time and frequency domains. The performances of control schemes are examined in terms of level of input tracking capability, sway angle reduction and time response specifications in comparison to SIFLC controller. Finally, a comparative assessment of the control techniques is discussed and presented.

Keywords—Double-pendulum-type overhead crane, anti-sway control, displacement control, single input fuzzy control, input shaping

1. Introduction

Various attempts in controlling cranes system based on open loop and closed-loop control system have been proposed. For example, open loop time optimal strategies were applied to the crane by many researchers [1,2]. Poor results were obtained in these studies because open-loop strategy is sensitive to the system parameters and could not compensate for the effect of wind disturbance. In other hand, feedback control which is well known to be less sensitive to disturbances and parameter variations has also been adopted for controlling the crane system. For example, PD controllers has been proposed for both position and anti-swing controls [3]. However, the performance of the controller is not very effective in eliminating the steady state error. In addition, an adaptive control strategy has also been proposed by Yang and Yang [4]. However, the control technique requires a nonlinear control theory which needs a complicated mathematical analysis.

The modern control approaches include fuzzy logic controller (FLC) has also been proposed for controlling the crane system by several researchers [5]. Although those modern control methods are very promising for DPTOC applications, they require substantial computational power because of complex decision making processes. However, it is possible to take full advantages of FLC for DPTOC application if the computational time of FLC is minimized. In this paper, the Single Input Fuzzy Logic Controller (SIFLC) is proposed. The SIFLC is a simplification of the Conventional Fuzzy Logic Controller (CFLC). It is achieved by applying the signed distance method [6] where the input to SIFLC is only one variable known as "distance". This is in contrast to the CFLC which requires an error and the derivative (change) of the error as its inputs. The reduction in the number of inputs simplifies the rule table to one-dimensional, allowing it to be treated as a single input single output (SISO) controller. As SIFLC can be treated as SISO controller, it can be a practical controller for DPTOC system. As the objective of the controlling crane system is to transfer a load from one location to another location, the position error and the velocity of the cart will be the input of the SIFLC. However, the SIFLC is limited for position control of cart and cannot cater for sway control. To overcome this problem, an input shaping schemes is incorporated to the system to suppress the sway of hook and load angle especially when the cart reaches the desired position [7]. The effectiveness of the proposed composite control method as well as the variety in mode selection for input shaper is evaluated to a nonlinear DPTOC model.

The rest of this paper is structured in the following manner. The next section provides a brief description of the double pendulum-type overhead crane system considered in this study. Section 3 describes the modelling of the system derived using Euler-lagrange formulation whilst Section 4 describes the design of SIFLC controller based on signed distance method. The design of input shaping schemes is explained in Section 5. Implementation results and robustness evaluation is reported in Section 6. Finally, concluding remarks are offered in the section 7 with the acknowledgement and references in section 8 and 9 respectively.

2. The Double-Pendulum-Type Overhead Crane System

The DPTOC system with its hook and load considered in this work is shown in Figure 1, where x is the cart position, m is the cart mass, and m_1 and m_2 are the hook and load mass respectively. θ_1 is the hook swing angle, θ_2 is the load swing angle, l_1 and l_2 are the cable length of the hook and load, respectively, and F is the cart drive force. In this simulation, the hook and load can be considered as point masses.

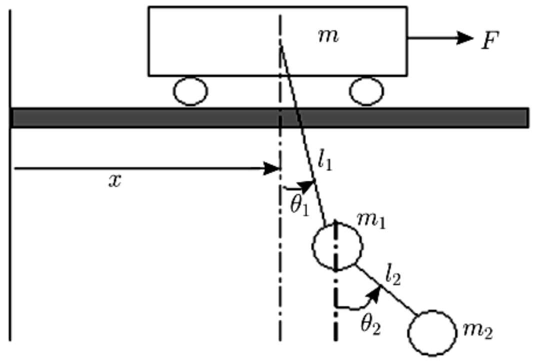


Fig.1: Description of the DPTOC system.

3. Dynamic Modeling of the Double-Pendulum Type Overhead Crane

This section provides a brief description on the modeling of the DPTOC system, as a basis of a simulation environment for development and assessment of the composite control techniques. The Euler-Lagrange formulation is considered in characterizing the dynamic behavior of the crane system incorporate payload.

By Lagrange's equations, the dynamic model of the DPTOC system, shown in Figure 1, is assumed to have the following form [8]

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \bar{\tau} \qquad (1)$$

where the matrices $M(q) \in \Re^{3\times3}$, $C(q,\dot{q}) \in \Re^{3\times3}$, and $G(q) \in \Re^{3}$ represent the inertia, Centrifugal-Coriolis terms, and gravity, respectively, and are defined as

$$M(q) = \begin{bmatrix} m + m_1 + m_2 & (m_1 + m_2)l_1 \cos\theta_1 & m_2 l_2 \cos\theta_2 \\ (m_1 + m_2)l_1 \cos\theta_1 & (m_1 + m_2)l_1^2 & m_2 l_1 l_2 \cos(\theta_1 - \theta_2) \\ m_2 l_2 \cos\theta_2 & m_2 l_1 l_2 \cos(\theta_1 - \theta_2) & m_2 l_2^2 \end{bmatrix} \qquad (2)$$

$$C(q,\dot{q}) = \begin{bmatrix} 0 & -(m_1 + m_2)l_1\dot{\theta}_1 \sin\theta_1 & -m_2 l_2 \dot{\theta}_2 \sin\theta_2 \\ 0 & 0 & m_2 l_1 l_2 \dot{\theta}_1 \sin(\theta_1 - \theta_2) \\ 0 & -m_2 l_1 l_2 \dot{\theta}_1 \sin(\theta_1 - \theta_2) & 0 \end{bmatrix} \qquad (3)$$

$$G(q) = \begin{bmatrix} 0 & (m_1 + m_2) g l_1 \sin\theta_1 & m_2 g l_2 \sin\theta_2 \end{bmatrix}^T \qquad (4)$$

where g is the gravity effect. The state vector q and the control vector $\bar{\tau}$, are defined as

$$q = \begin{bmatrix} x & \theta_1 & \theta_2 \end{bmatrix}^T$$

$$\bar{\tau} = \begin{bmatrix} F & 0 & 0 \end{bmatrix}^T$$

After rearranging (1) and multiplying both sides by M^{-1}, one obtains

$$\ddot{q} = M^{-1}(-C\dot{q} - G + \bar{\tau}) \qquad (5)$$

where M^{-1} is guaranteed to exist due to $\det(M) > 0$.

In this study the values of the parameters are defined as
m=5 kg, m_1=2 kg, m_2=5 kg, l_1=2 m, l_2=1 m and g=9.8 m-s^{-2} [9].

4. Single Input Fuzzy with Command Shaping Schemes

Fuzzy Logic controller (FLC) is a linguistic-based controller that tries to emulate the way human thinking in solving a particular problem by means of rule inferences. Typically, a FLC has two controlled inputs, namely error (e) and the change of error ($\dot{e}$). Its rule table can be created on a two-dimensional space of the phase-plane ($e, \dot{e}$) as shown in Table 1. It is common for the rule table to have the same output membership in a diagonal direction. Additionally, each point on the particular diagonal lines has a magnitude that is proportional to the distance from its main diagonal line L_Z. This is known as the Toeplitz structure. The Toeplitz property is true for all FLC types which use the error and its derivative terms, namely $\dot{e}, \ddot{e}$... and $e^{(n-1)}$ as input variables [10].

Table 1. Rule Table with Toeplitz Structure

$\dot{e}$ \ e	**PL**	**PM**	**PS**	**Z**	**NS**	**NM**	**NL**
NL	Z	NS	NM	NL	NL	NL	NL
NM	PS	Z	NS	NM	NL	NL	NL
NS	PM	PS	Z	NS	NM	NL	NL
Z	PL	PM	PS	Z	NS	NM	NL
PS	PL	PL	PM	PS	Z	NS	NM
PM	PL	PL	PL	PM	PS	Z	NS
PL	PL	PL	PL	PL	PM	PS	Z

By observing the consistent patterns of the output memberships in Table 1, there is an opportunity to simplify the table considerably. Instead of using two-variable input sets ($e, \dot{e}$), it is possible to obtain the corresponding output, u_0 using a single variable input only. The significance of the reduction was first realised by Choi et al. and is known as the signed distance method [6]. The method simplifies the number of inputs into a single input variable known as distance, d. The distance represents the absolute distance magnitude of the parallel diagonal lines (in which the input set of e and $\dot{e}$ lies) from the main diagonal line L_Z. To derive the distance, *d* variable, let $Q(e_0, \dot{e}_0)$ be an intersection point of the main diagonal line and the line perpendicular to it from a known operating point $P(e_1, \dot{e}_1)$, as illustrated in Figure 2.

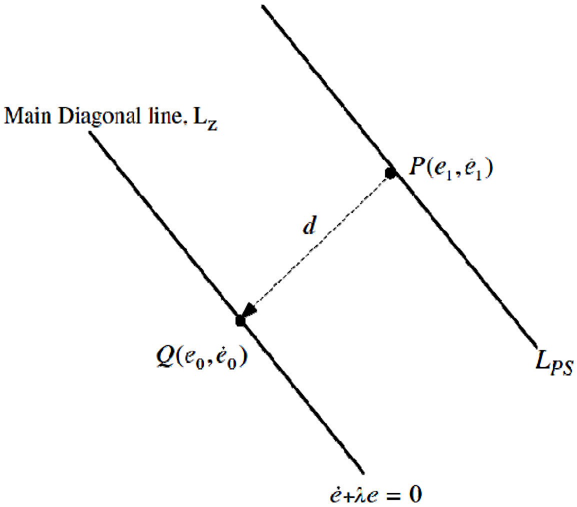


Fig.2: Derivation of distance variable.

It can be noted that the main diagonal line can be represented as a straight line function, i.e.:

$$\dot{e} + \lambda e = 0 \tag{6}$$

In equation (6), variable λ is the slope magnitude of the main diagonal line L_Z. The distance d from point *P* $(e_1, \dot{e}_1)$ to point $Q(e_0, \dot{e}_0)$, can be obtained as [10]:

$$d = \frac{\dot{e} + \lambda e}{\sqrt{1 + \lambda^2}} \tag{7}$$

The derivation of distance input variable resulted in a one-dimensional rule table, in contrast to a two-dimension table required by the conventional FLC. The reduced rule table is depicted in Table II, where L_{NL}, L_{NM} L_{NS}, L_Z, L_{PS} L_{PM} and L_{PL} are the diagonal lines of Table 2. The diagonal lines correspond to the new input of this rule table, while NL, NM, NS, Z, PS, PM and PL represent the output of corresponding diagonal lines. As can be realized, the control action of FLC is now exclusively determined by *d*. It is therefore appropriate to called it the Single Input FLC (SIFLC).

The overall structure of SIFLC, derived from the signed distance method can be depicted as a block diagram in Figure 3. Two system state variables *e* (position error) and $\dot{x}$ (velocity of the cart) are selected as the feedback signal. The input to the FLC block is the distance variable *d*, while the output from FLC block is the change of control output $\dot{u}_0$. The final output of this FLC is obtained by multiplying $\dot{u}_0$ with the output scaling factor, denoted as *r*. The output equation can be written as:

$$u = \dot{u}_0 r \tag{8}$$

Table 2. The Reduced Rule Table using The Signed Distance Method

d	L_{NL}	L_{NM}	L_{NS}	L_Z	L_{PS}	L_{PM}	L_{PL}
u_0	NL	NM	NS	Z	PS	PM	PL

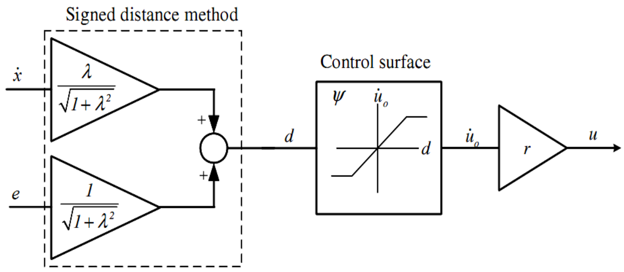


Fig. 3: SIFLC structure for DPTOC with linear control surface

5. Input Shaping Control Schemes

Input shaping technique is a feed-forward control technique that involves convolving a desired command with a sequence of impulses known as input shaper. The shaped command that results from the convolution is then used to drive the system. Design objectives are to determine the amplitude and time locations of the impulses, so that the shaped command reduces the detrimental effects of system flexibility. These parameters are obtained from the natural frequencies and damping ratios of the system.

For the case of positive amplitudes, each individual impulse must be less than one to satisfy the unity magnitude constraint. In order to increase the robustness of the input shaper to errors in natural frequencies, the positive Zero-Sway-Derivative-Derivative (ZSDD) input shaper, is designed by solving the derivatives of the system vibration equation. This yields a four-impulse sequence with parameter as

$$t_1 = 0,\ t_2 = \frac{\pi}{\omega_d},\ t_3 = \frac{2\pi}{\omega_d},\ t_4 = \frac{3\pi}{\omega_d}$$

$$A_1 = \frac{1}{1+3K+3K^2+K^3},\ A_2 = \frac{3K}{1+3K+3K^2+K^3}$$

$$A_3 = \frac{3K^2}{1+3K+3K^2+K^3},\ A_4 = \frac{K^3}{1+3K+3K^2+K^3} \tag{9}$$

where

$$K = e^{-\zeta\pi / \sqrt{1-\zeta^2}},\quad \omega_d = \omega_n\sqrt{1-\zeta^2}$$

(ω_n and ζ representing the natural frequency and damping ratio respectively) and t_j and A_j are the time location and amplitude of impulse j respectively. The selection of natural frequency modes is very crucial in sway reduction. In this study, three types of mode combination are proposed to evaluate the performance of sway reduction and speed of the cart position response.

6. Implementation and Results

In this investigation, composite control schemes for trajectory tracking capability and sway suppression are examined. Initially, a SIFLC controller is designed to control the cart position. This is then extended input shapers with several mode combinations for control of sway of the system. The natural frequency was obtained by exciting the cart position with an unshaped reference input under SIFLC controller. The input shapers were designed for pre-processing the trajectory reference input and applied to the system in a closed-loop configuration, as shown in Figure 4. In this study, the cart position of DPTOC is required to follow a unit step trajectory of 5 m. The responses of the DPTOC system to the unshaped trajectory reference input were analyzed in time-domain and frequency domain (spectral density). The first three modes of sway frequency of the system are considered, as these dominate the dynamic of the system. These results were considered as the system response to the unshaped input under tracking capability and will be used to evaluate the performance of the input shaping schemes with three types of mode combination.

Implementation results with SIFLC controller have shown that the steady-state cart position trajectory of 5 m for the DPTOC system was achieved within the rise and settling times and overshoot of 1.979 s, 5.354 s and 7.44 % respectively. However, a noticeable amount of oscillation occurs during movement of the cart. It is noted from the sway of hook and load angle response with a maximum residual of ±0.6 rad and ±0.8 rad respectively. Moreover, from the PSD of both hook and load swing angle response, the sway frequency is dominated by the first three modes, which is obtained as 0.294 Hz, 1.079 Hz and 1.668 Hz. The closed loop parameters with the SIFLC control will subsequently be used to design and evaluate the performance of composite controllers with input shapers. The application of input shaper with single mode, first two modes and three modes of sway frequency are applied to the DPTOC system. With the exact natural frequency of 0.294 Hz, 1.079 Hz and 1.668 Hz, the time locations and amplitudes of the impulses for the proposed input shapers scheme were obtained by solving equation (9).

The system responses of the DPTOC system to the shaped trajectory input with exact natural frequency using SIFLC with single mode, first two modes and three modes shapers are shown in Figure 5. Table 3 summarises the level of sway reduction of the system responses at the different combination of modes in comparison to the SIFLC control. Higher levels of sway reduction were obtained using SIFLC with three modes shaper as compared to the case with single and two modes shaper. This can be clearly observed from the response of both hook and load sway angle in Figure 5(b). However, with single mode shaper, the cart position response as shown in Figure 5(a) is faster as compared to higher number of mode combinations. It shows that the speed of the system response reduces with the increase in number of modes as well as number of impulse sequence. The corresponding rise time, settling time and overshoot of the cart position response using SIFLC control with single mode, first two modes and three modes shapers is depicted in Table 3. It is also noted that a slower cart position response for SIFLC with input shaping control schemes, as compared to the SIFLC control, was achieved.

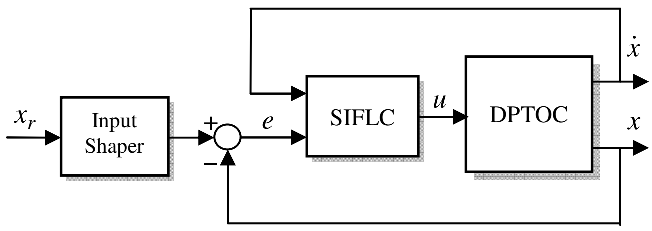
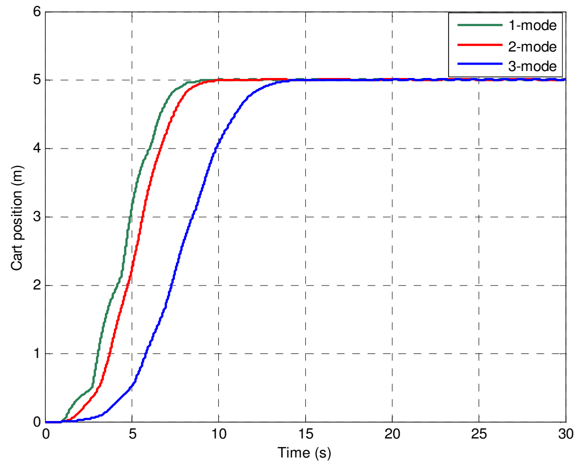


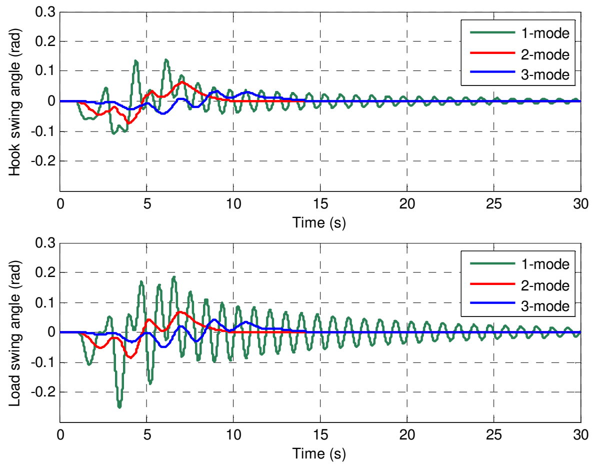
Fig. 4: SIFLC with input shaping control structure.

Table 3. Level of sway reduction of the hook and load swing angle and specifications of cart position response

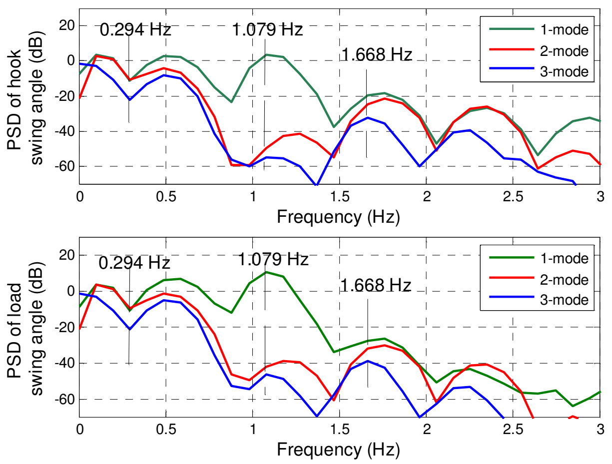
Types of shaper	Swing angle	Attenuation (dB) of sway of the cable			Specification of cart position response		
		Mode 1	Mode 2	Mode 3	Rise time (s)	Settling time (s)	Overshoot (%)
1-mode	Hook swing angle, θ_1	32.54	0.25	-4.89	3.958	6.192	0.12
	Load swing angle, θ_2	32.90	0.83	12.25			
2-mode	Hook swing angle, θ_1	31.49	53.19	0.19	4.315	6.975	0.02
	Load swing angle, θ_2	31.85	53.05	16.95			
3-mode	Hook swing angle, θ_1	43.52	58.28	7.48	6.048	10.780	0.00
	Load swing angle, θ_2	43.46	57.97	23.78			



(a) Cart position.



(b) Hook and load swing angle.



(c) PSD of hook and load swing angle.

Fig. 5: Response of the DPTOC with composite SIFLC and input shaping.

7. Conclusions

The development of composite control schemes based on SIFLC control with single mode, first two modes and three modes shapers for input tracking and sway suppression of a DPTOC system has been presented. The performances of the control schemes have been evaluated in terms of input tracking capability, level of sway reduction, time response specifications and robustness. Acceptable performance in input tracking control and sway suppression has been achieved with proposed control strategies. Moreover, a significant reduction in the system sway has been achieved with the composite controllers regardless of the number of modes in the input shapers design. A comparison of the results has demonstrated that the SIFLC control with higher number of input shaper modes provide higher level of sway reduction as compared to the cases using lower number modes. However, with lower number of modes, the speed of the response is slightly improved at the expenses of decrease in the level of sway reduction. It is concluded that the proposed composite controllers are capable of reducing the system sway while maintaining the input tracking performance of the DPTOC.

8. Acknowledgment

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9. References

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