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Implementation of Internal Model Control (IMC) in Crane Systems

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***Abstract*: In the past decades industrial cranes have been increasingly utilized as indispensable engineering equipment in various fields. The under actuated structure of the crane makes it hard to control. The achievement of both transporting trolley to target position and reducing payload swing is not always easy in real cases. The main objective of this paper is to use IMC for controlling the trolley position and swing motion. The analysis of the crane control using IMC is compared with conventional PID and PD controller. The analysis shows that IMC significantly increases the control speed and the accuracy, and also has good tracking ability for the set-point control, combining with improved robustness for disturbance and model's time-varying character.**

***Keywords*: Crane, Internal Model Control (IMC), under actuated structure.**

1. Introduction

The main purpose of control of an overhead crane is to transport the load to the desired location with less swing. Most of the crane used in industry results in a swing movement when payload is suddenly stopped after a fast motion. The overhead crane are used mainly in the factories mainly in hazardous areas like nuclear power plant due to its low cost, easy assembly, precise positioning of load and less maintenance. The swing motion can be decreased to some extent by adjusting the speed of the motor but it will be time-consuming process. A skilful operator is needed to control both the position and swing manually. The lack of efficiency in controlling the crane also might cause problems and create harm to the people and the surroundings. Various methods was done on cranes system based on open loop control system. Earlier open loop time optimal strategies were applied to the crane system by many researchers such as discussed in [2],[3]. The results showed that open loop approach is sensitive to the system parameters and could not compensate for disturbances due to wind. Another importance of open loop method is the input shaping introduced by Karnopp [4], Teo [5] and Singhose [6]. However the input shaping method is also again an open-loop approach. Hubbel et al. [7] used an open-loop method to control the movement of the crane. In this open loop control strategy, the input control profile was determined in such a way that unwanted oscillations And residual pendulations were neglected. However their approach was applicable, but the open loop control technique is not robust to disturbances and parameter uncertainties [8]. Moreover, a feedback PID anti-swing controller is developed in [9] for controlling overhead crane. Ahmad et al. [10] used a hybrid input-shaping approach to control of the crane. Wahyudi and Jalani [11] introduced fuzzy logic feedback control technique to control the crane system. They also presented an optimal control technique is used in [12] to control the oscillatory motion of the crane. Here, minimum energy of the system and also integrated absolute error of the payload angle are considered as their optimization criterion. Zhao and Gao [13] studied the control of the overhead crane. They introduced a fuzzy control strategy to control the input delay and actuator saturation of the system. Nazemizadeh et al. [14] studied tracking control of the crane. Furthermore, Nazemizadeh [15] presented a PID tuning method for tracking control of a crane.
In this paper, overhead crane is provided with a IMC to control both swing and position of the crane and the results are compared with conventional PD and PID control. The structure of this paper is as follows. The modelling of the crane is explained in section 2. Section 3 discusses about the crane with conventional PD and PID controller. Section 4 discusses about the crane with IMC. Simulation results is given in section 5. Conclusion is discussed in section 6.

2. Modelling of crane

Figure 1 represents a schematic diagram of the crane considered in this paper. Due to the fact that only two dimensional motion of crane is considered in this paper, there are two independent coordinates namely y and θ_y to describe the trolley position and the swing angle of the payload respectively. Since the mass of the rope used in the crane is small enough as compared to the payload mass m_p, it is assumed to be as massless. The non-linear dynamic model of overhead crane prototype is derived by using Lagrange equations.

$$(m_t + m_p)\ddot{y} = F_y + m_p l(\dot{\theta}_y^2 \sin\theta_y - \ddot{\theta}_y \cos\theta_y) \tag{1}$$

$$\cos\theta_y \ddot{y} + l\ddot{\theta}_y = -g\sin\theta_y \tag{2}$$

By assuming small value of θy, the following linearized model of the crane is found out.

$$(m_p + m_t)(\ddot{y}) + m_p l(\ddot{\theta}_y) = F_y \tag{3}$$

$$\ddot{y} + l\ddot{\theta}_y + g\theta_y = 0 \tag{4}$$

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In the equation given above, m_t is the mass of the trolley, m_p is mass of the payload, l is the length of the rope, y is the position of the trolley, θy is the swing angle and Fy is the force supplied by the dc motor. Thus the state space model of the crane system can be obtained as

$$\dot{X} = Ax + Bu \tag{5}$$

$$Y = Cx + Du \tag{6}$$

Where

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{m_p g}{m_t} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -\frac{(m_t+m_p)g}{m_t l} & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 1/m_t \\ 0 \\ -1/m_t l \end{bmatrix} \qquad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \qquad D = [0]$$

$$X = \begin{bmatrix} y & \dot{y} & \theta_y & \dot{\theta}_y \end{bmatrix}^T$$

Table 1
Crane and Motor parameters

Symbol	Value	Unit
m_p	0.23	Kg
m_t	1.073	Kg
L	0.3302	m
G	9.81	m/s^2
R	0.006	m
R	2.6	Ω
L	2.5×10^{-3}	H
J	2×10^{-5}	Kg/m^2
B	5×10^{-5}	Nms/rad
k_b	0.00767	Nm/A
k_t	0.00767	Vs/rad

The translational motion of the trolley is supplied by DC motor. Therefore, to find out the entire model of the crane, the motor dynamic is modeled according to equivalent DC motor circuit. The equivalent circuit of DC motor has an armature resistance R, inductance L, motor inertia J, torque constant k_t, input voltage to the dc motor V, armature current I and damping constant B. The rotational motion is transformed to translational motion through the mechanical part (pulley or gear) with radii of r. The dynamics of dc motor circuit is given below by the following equations

$$V = RI + L\frac{dI}{dt} + k_b\theta \tag{7}$$

$$T = k_t I \tag{8}$$

$$J(\ddot{\theta}) + B(\dot{\theta}) = T \tag{9}$$

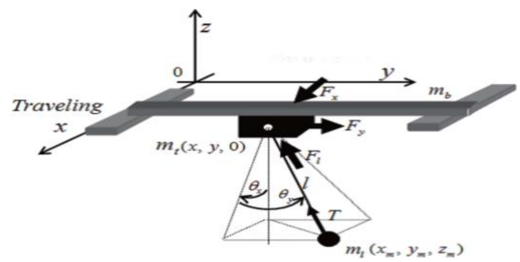

Fig. 1. Crane model

3. Crane control with PID and PD controller

The conventional PID and PD controllers are used to analyze the ability of the proposed model-based soft sensor. The function of the controller is to control the payload position Y(s) so that it moves to the desired position $Y_r(s)$ as fast as possible without larger swing angle$\theta_y(s)$. A PID controller is used in the system to control the position of the crane, while a PD controller is used for controlling the swing angle. The values of the controller gains used in PID and PD controllers are designed and optimized with simulation model by using Simulink response optimization library block. It is mainly a numerical time domain optimizer developed under MATLAB/Simulink software. Hence the response obtained by the Simulink optimization library block helps in time-domain-based control design by setting the desired value of overshoot, settling time and steady state error. In order to analyze the motion of the crane quickly with small value for overshoot, the PID controller is optimized. Moreover, in order to reduce the value of the swing angle quickly, the PD controller is optimized. Thus there are five parameters to be optimized in order to have satisfactory control performance. The parameters, K_p, K_i, K_d, K_{ps} and K_{ds} which are the proportional, integral and derivative gains for the position control and proportional, derivative gains for the anti-swing control. The optimization to obtain PID and PD controller gains for position and anti-swing crane control was done by using Ziegler Nichols tuning method. Based on the result, the gains of K_p, K_i, K_d, K_{ps} and K_{ds} are shown in Table 2.

Table 2
Optimized PID and PD position and anti-swing gains

K_p	K_i	K_d	K_{ps}	K_{ds}
140.4	0.7	136.5	43.5	12.8

4. Internal Model Control (IMC)

The theory of the internal model control has been introduced for years, but the application in industrial control is just in recent years. The key is how to get the process model conveniently and apply IMC in the system easily. This paper introduces to design the IMC control.

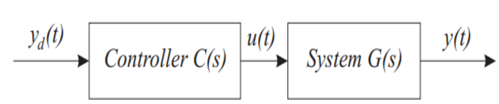

Fig. 2. IMC controller

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Suppose $\tilde{G}(s)$ is a model of G(s). C(s) is considered as the inverse of the model: $C(s) = \tilde{G}(s)^{-1}$ and assuming that $\tilde{G}(s) = G(s)$ then the output y(t) will track the reference input $y_d(t)$ perfectly.

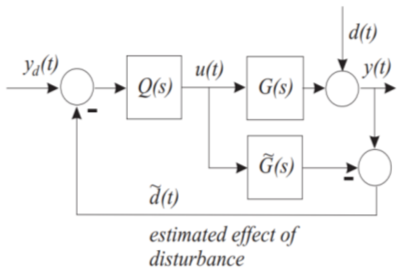

Fig. 3. Block diagram of IMC

The IMC system is internally stable if and only if both the functions G(s) and Q(s) are stable (if $\tilde{G}(s) = G(s)$).

$$Q(s) = C(s)/(1 + \tilde{G}(s)C(s)) \tag{11}$$

The importance of IMC lies in the fact that it allows us to concentrate on the controller design without having to be concerned with stability provided that the process model $\tilde{G}(s)$ is a perfect representation of the stable process transfer function G(s). The IMC design procedure consists of two steps: The first step will insure that Q(s) is stable and causal, the second step will require Q(s) to be proper. Factor the model function into two parts $\tilde{G} = \tilde{G}+ \tilde{G}-$. $\tilde{G}+$ contains all non-minimal phase elements of the plant model: all RHP zeros and time delays. The factor $\tilde{G}-$ is minimum phase and invertible, yielding an (intermediate) IMC controller: $\tilde{Q}(s) = \tilde{G}^{-1}-$ which is stable and causal (not necessarily proper). Augment $\tilde{Q}(s)$ with a low pass filter f(s) such that the final IMC controller $Q(s) = \tilde{}\, Q(s)f(s)$ is also proper, yielding: $T(s) = \tilde{G}\tilde{Q}f$, $S(s) = 1 - \tilde{G}\, \tilde{Q}f$. The inclusion of the filter transfer function means that filter forms is needed that allow for no offset to type 1 and 2 inputs. For zero offset for steps, T (0) = 1 is required, which requires that $Q(0) = \tilde{G}^{-1}(0)$ and forces: f(0) = 1. A common method is: $f(s) = 1/(\lambda s + 1)^n$ where the order n is selected large enough to make Q proper, while λ is an adjustable parameter which determines the speed-of-response. λ is a tuning parameter to avoid excessive amplification of output noise and to accommodate for modelling errors. Thus the IMC is developed in series with a low pass filter. It provides an easy framework for robust control system. IMC is an effective method for designing and implementing robust controllers.

5. Simulation results

MATLAB software package is used in the crane system to determine the response of the system. The Simulink model of the system with the optimized values of PD and PID controller gains is created in MATLAB. The Simulink model of the system is developed. The figure 4 shows the position and swing angle control using optimized values for PD and PID controller. From Fig. 5 and Fig. 6, the system is regulated at 5 sec and 2 sec respectively and the system consists of small number of overshoot and undershoot when compared to PD and PID controller. The system is precisely regulated at this condition. IMC control the position and swing without undershoot in spite of the disturbances.

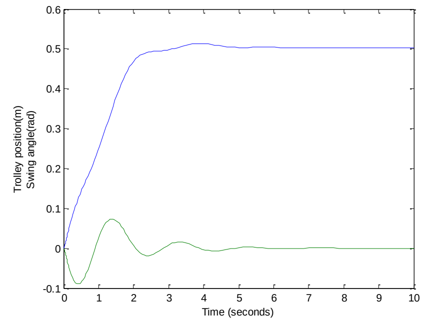

Fig. 4. Position and swing angle control using PD and PID controller

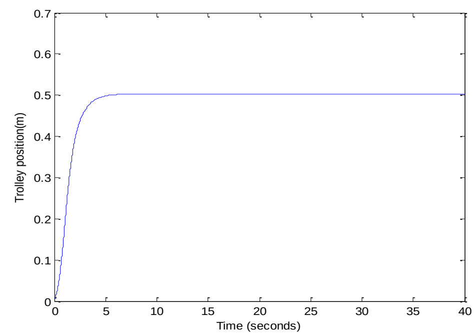

Fig. 5. Position control using IMC

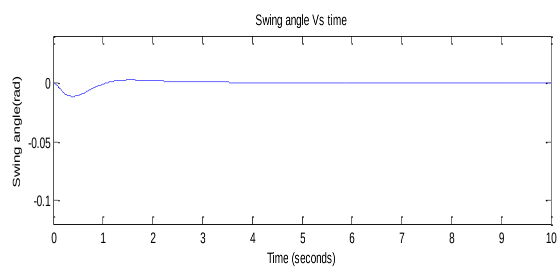

Fig. 6. Swing angle control using IMC

6. Conclusion

This paper presented the Implementation of Internal Model Control (IMC) In Crane Systems.

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