Journal of Engineering and Applied Sciences 13 (Special Issue 3): 3308-3313, 2018
ISSN: 1816-949X

Terminal Synergetic Control of Crane System

[1]Djamila Zehar, [1]Khier Benmahammed, [1]Khalissa Behih and [2]Aida Cherif
[1]Department of Electrical Engineering, LSI Laboratory, Universtity of Setif, Setif, Algeria
[2]Department of Electromechanical, Universtity of Bordj Bou Arreridj, Bordj Bou Arreridj, Algeria

Abstract: Crane system is a manufacturing structure, used in bridges for buildings and in industrial transport for materials, to transfer suspended and heavy loads. Several domains and industrial use this structure which implies searches to achieve its good control. Automatic control for uncertain and perturbed crane has recently a big challenge and gives solutions where manually control strategies fail and cause accidents. The objective of control is to achieve good performances (precision, fast response time and stability when tracking a given trajectory). Recently researchers give attention to robust control such that sliding mode technique this one still has the problem of chattering which limits its applications. In this research, we propose the synergetic control of crane system which is a non-linear robust control, allows forcing the system to evolve towards an equilibrium point, according to a chosen dynamics while maintaining the same performances as in sliding mode control without chattering. To guarantee a finite time stability of the crane and faster response, we added the terminal term to the macro variables in the developed synergetic control. The development is composed of two levels in the first one, we introduce the macro variables and in the second one we combine these macro variables with a linear relation. Stability analyses is given and simulation results show the effectiveness of the propose strategy where good performances are achieved compared to terminal sliding mode control results.

Key words: Synergetic control, terminal technique, finite time convergence, stability, crane system, underactuated system

INTRODUCTION

Generally, crane system consists of bridge travelling mechanism and lifting trolley which travels on the carrier track. In view of rigidity of system structure, crane is widely used for transportation of heavy material in industries, buildings construction, warehouse, etc. During the development over the last decade, depending on the freight which has to handle, the transfer distance, the weight, cranes are readily adapted and specific classes of crane has been established.

Many years ago, control of canes was manually, it based on swing motion. The structure of these systems is developed and becomes larger, faster and higher this new structure and swaying phenomenon might cause accident and damage materials and people. To resolve this problem, new and modern controllers are applied to uncertain and perturbed crane system, to guarantee a high precision, to reach the desired position and to truck a given trajectory with a faster response.

According to the model of crane system, we can mention two classes of the control strategy. Control for the linearized model of crane system and control for the non-linear model.

Linearized crane system was controlled using many techniques, many problems of control have been addressed such that the path planning problem as by Hamalainen *et al*. (1995) and Hong *et al*. (2000) the open-loop time optimisation strategy as by Manson (1992) the feedback control with PD controller as by Omar (2003) the PID controller has also been developed by Nazemizadeh (2013) unfortunately these problems couldn't achieve the good control performance where the PD, the path planning and the optimisation strategies can't achieve the good precision by eliminating the steady state error and open-loop strategy is sensitive to the system parameters change and can't compensate the effect of disturbance, also the PID controller can't be effective when the actuator saturates. Generally, the linear control, lose the property of precision of information about position and load swing of the crane system, where uncertainties and perturbations decrease system performances.

Several non-linear control strategies have been developed, to overcome the disadvantages encountered in linear control. Intelligent structure as fuzzy logic controllers have been used to control a special type of cranes as by Lee and Cho (2001) which could eliminate swing problem of the payload. In order to get a good

Corresponding Author: Djamila Zehar, Department of Electrical Engineering, LSI Laboratory, Universtity of Setif, Setif, Algeria

position control, other researchers combine the PID and the fuzzy logic controller. In general these strategies need to have an exact model of the crane which can be done just with an expert engineer in this context, we cite the study of Chang (2007) where he proposed an adaptive fuzzy controller without any information about the crane system. Robust control arises to be adopted in order to deal with external perturbations and uncertainties. Several works have been done using Sliding Mode Control (SMC) as by Shyu *et al*. (2005) when the researchers define a sliding surface coupling both sub-systems and by Wang *et al*. (2007) where they used an incremental hierarchical SMC controller of crane system and the research of Park *et al*. (2008) using a divisibility to design a fuzzy sliding surface for the trolley sub system of the crane and the one of Qian *et al*. (2011) where a combination of fuzzy regulator and SMC is developed for controlling an overhead crane system. By using these control approaches, convergence to the equilibrium point is asymptotic and not fast enough. Terminal Sliding Mode (TSMC) control could enable the finite time reachability as presented by Yu and Zhihong (1998) and Liu and Wang (2012). To get a faster convergence of the crane, some researchers assume to use and to applying the fast terminal sliding mode control as by Singh *et al*. (2016) where authors can achieve a good performances, unless for chattering phenomenon that remains specially in control signal which is the major disadvantage of the SMC. To overcome this problem, we propose in this research, the terminal synergetic control, this one belongs to robust control domain, it allows getting similar performances as in SMC without chattering, it has the properties of order reduction and decoupling and it is more appropriate for numerical implementaton, since, it research with constant frequency. Synergetic control was first introduced by Russian researchers (Kolesnikov *et al*., 2000) and it was applied for some type of systems and in several areas such that: power systems as by Jiang (2007) mechanical systems as by Zhai *et al*. (2015) and chaotic systems as by Harmas (2016).

Our contribution is to combine the fast terminal technique and the synergetic control for underactuated crane, where the macro-variables are defined in the first level for each subsystem in the second level a linear combination of these macro-variables are constructed. This technique of control, assures a faster and finite time convergence and high precision, without chattering.

MATERIALS AND METHODS

Mathematical model of the system: The overhead crane is a second order underactuated system; its structure is given in Fig. 1, it consists of a trolley of mass M and a load mass m suspended to the trolley by a rope of length L. the swing angle of the load with respect to the vertical line is q, the trolley position with respect to the origin is x and the force applied to the trolley is f. We have the following assumptions:

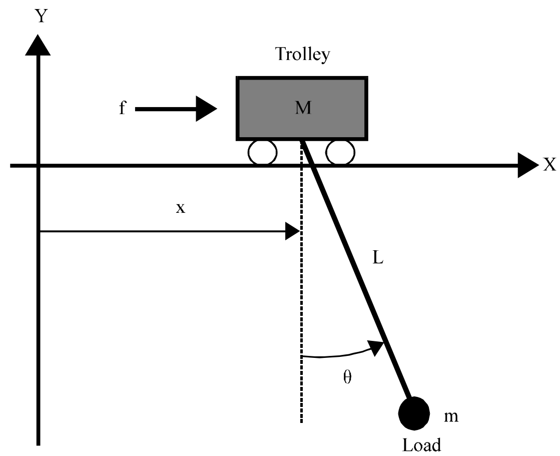

Fig. 1: Overhead crane system

- The trolley and the load can be regarded as point masses
- Friction force which may exist in the trolley and the elongation of the rope due to the tension can be neglected
- The trolley moves along the rail and the load moves in the x-y plan

The control objective of the overhead crane is to move the trolley to its destination and complement anti-swing of the load at the same time.

Using lagrange's method, we can obtain the following lagrangian equation related to the generalised coordinate q as:

$$\frac{d}{dt}=\left(\frac{\partial L}{\partial q}\right)-\frac{\partial L}{\partial q}=U \quad (1)$$

Where:

$q=[x,\theta]^T\in R^2$ = The generalised coordinates

U = The external force

The dynamic model of the overhead crane system is given by:

$$(m+M)\ddot{x}+mL\left(\ddot{\theta}\cos\theta-\dot{\theta}^2\sin\theta\right)=U \quad (2)$$

$$\ddot{x}\cos\theta+L\ddot{\theta}+g\sin\theta=0 \quad (3)$$

g is the gravitational acceleration, Eq. 2 and 3 can be reformulated in the following form:

$$\ddot{x} = f_x(x, \dot{x}, \theta, \dot{\theta}) + b_x(x, \theta)U \tag{4}$$

$$\ddot{\theta} = F_\theta(x, \dot{x}, \theta, \dot{\theta}) + b_\theta(x, \theta)U \tag{5}$$

Where:

$$f_x(x, \dot{x}, \theta, \dot{\theta}) = \frac{mL\dot{\theta}^2 \sin\theta + mg\sin\theta\cos\theta}{M + m\sin^2\theta}$$

$$f_\theta(x, \dot{x}, \theta, \dot{\theta}) = -\frac{(m+M)g\sin\theta + mL\dot{\theta}\sin\theta\cos\theta}{(M + m\sin^2\theta)L}$$

$$b_x(x, \theta) = \frac{1}{M + m\sin^2\theta}$$

$$b_\theta(x, \theta) = -\frac{\cos\theta}{(M + m\sin^2\theta)L}$$

The dynamic of the overhear crane system can be expressed in the following state space model:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f_x(X) + b_x(X)U \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = f_\theta(X) + b_\theta(X)U \end{cases} \tag{6}$$

Here: $x_1 = x, x_3 = \theta$ and $[x_1, x_2, x_3, x_4]^T$, the vector of outputs is given by: $y = [x_1, x_3]^T$.

Synergetic control procedure: Synergetic control arose since few years ago has been developed and well used by the automation control community. Synergetic control follows the same steps in conception of the control law as in sliding mode control and can achieve same performances which prove its robustness against uncertainties and extern perturbations. The advantage of this control is that the control signal is smooth and continuous, so, we don't have the problem of chattering as in SMC.

Synergetic control uses non-linear model (we don't need a linearization procedure) where the control law is constructed using a macro-variable (Harmas, 2016; Santi *et al*., 2003). We consider the n-order non-linear dynamic system described by Eq. 7:

$$\frac{dx(t)}{dt} = f(X, U, t) \tag{7}$$

Where:
X = The state space vector
U = The control input

For simplicity, for a basic synthesis of synergetic control, we will consider a single input output system. Control synthesis begins by a suitable choice of a macro-variable function as in Eq. 8:

$$\Psi = \Psi(X, t) \tag{8}$$

where, ψ and $\psi(X, t)$ designate designer chosen macro-variable and a corresponding state variables and time dependent function. The system is forced to remain in a desirable manifold, even in presence of undesirable disturbances or parametric uncertainties as the following Eq. 9:

$$\psi = 0 \tag{9}$$

A large choice is available to the designer in selecting the macro-variable features accordingly with the control objectives and practical physical constraints. The macro-variable which may be a simple linear combination is forced to evolve accordingly to designer imposed constraint of the general following form:

$$T\dot{\psi} + \psi = 0, \; T > 0 \tag{10}$$

Control parameter T dictates convergence rate towards the selected manifold given by Eq. 9. The appropriate control law is obtained using straightforward mathematical following steps:

$$\frac{d\psi(X, t)}{dt} = \frac{d\psi(X, t)}{dX} \cdot \frac{dx}{dt} \tag{11}$$

Using Eq. 7, 8 and 10 leads to the following Eq. 12:

$$T\frac{d\psi(X, t)}{dt} f(X, U, t) + \psi(X, t) = 0 \tag{12}$$

From Eq. 12, we have the following control law:

$$U = g(X, \psi(x, t), T, t) \tag{13}$$

We can see clearly that the control law U depends not only on system variables but on parameter T and macro-variable ψ as well which allows us choosing controller parameters depending on the real system model.

We can achieve a closed-loop system global stability even with uncertainties where states of system reach a pre-chosen manifold and remain on it, this manifold and macro-variables are defined carefully and soundly (Liu and Hsiao, 2013).

Fast terminal syneretic contol of the overhead crane system: Fast terminal synergetic control requires defining non-linear macro variables. For the overhead crane system, we can define at the first level, two macro variables for each sub-system as follows:

$$\psi_1 = e_2+k_1e_1+\beta_1e_1^{q_1/p_1} \tag{14}$$

$$\psi_2 = e_4+k_2e_3+\beta_2e_2^{q_2/p_2} \tag{15}$$

where, $e_1 = x_1\text{-}x_{1d}$, $e_2 = x_2\text{-}x_{1d}$, $e_3 = x_3\text{-}x_{1d}$, $e_4 = x_4\text{-}x_{3d}$ and $X_d = [x_{1d}, x_{3d}]^T$ is the vector of desired state variables. k_1, k_2, β_1 and β_2 are positive constants, q_1, p_1, q_2 and p_2 are odd positive constants satisfying the following conditions: $p_1>q_1$ and q_2. In the second level, we define the linear combination of these macro variables as in Eq. 16:

$$\psi = \sigma_1\psi_1+\sigma_2\psi_2 \tag{16}$$

where, $\sigma_1>0$ and $\sigma_2>0$. From Eq. 10, we get:

$$\begin{aligned} &T(\sigma_1(\dot{e}_2+k_1\dot{e}_1+\beta_1\frac{q_1}{p_1}\dot{e}_1e_1^{q_1/p_1-1})+ \\ &\sigma_2(\dot{e}_4+k_2\dot{e}_3+\beta_2\frac{q_2}{p_2}\dot{e}_3e_3^{q_2/p_2-1}))+\psi = 0 \end{aligned} \tag{17}$$

Substituting the derivatives from Eq. 6 and solving Eq. 17, we can get the following control law:

$$\begin{aligned} U=&\frac{-1}{\sigma_1b_1+\sigma_2b_2}(\sigma_1\left(f_1-\ddot{x}_{1d}+k_1e_2+\beta_1\frac{q_1}{p_1}e_2e_1^{q_1/p_1-1}\right)+ \\ &\sigma_2\left(f_2-\ddot{x}_{3d}+k_2e_4+\beta_2\frac{q_2}{p_2}e_4e_3^{q_2/p_2-1}\right)+\frac{\psi}{T}) \end{aligned} \tag{18}$$

Stability is studied using Lyapunov function as follows:

$$V = \frac{1}{2}\psi^2 \tag{19}$$

This implies that:

$$\dot{V} = \psi\dot{\psi} \tag{20}$$

From Eq. 10, we get:

$$\dot{V}=\psi\left(-\frac{\psi}{T}\right)=-\frac{\psi^2}{T} \tag{21}$$

From Eq. 21, we get $\dot{V}<0$ which means that the stability of the system is guaranteed.

RESULTS AND DISCUSSION

In this study, we apply the proposed control strategy to an overhead crane, using MATLAB environment where the parameters of the system are: M = 1 kg, m = 0.8 kg, L = 0.3 kg, g = 9.8 m/sec^2 and the control parameters are:

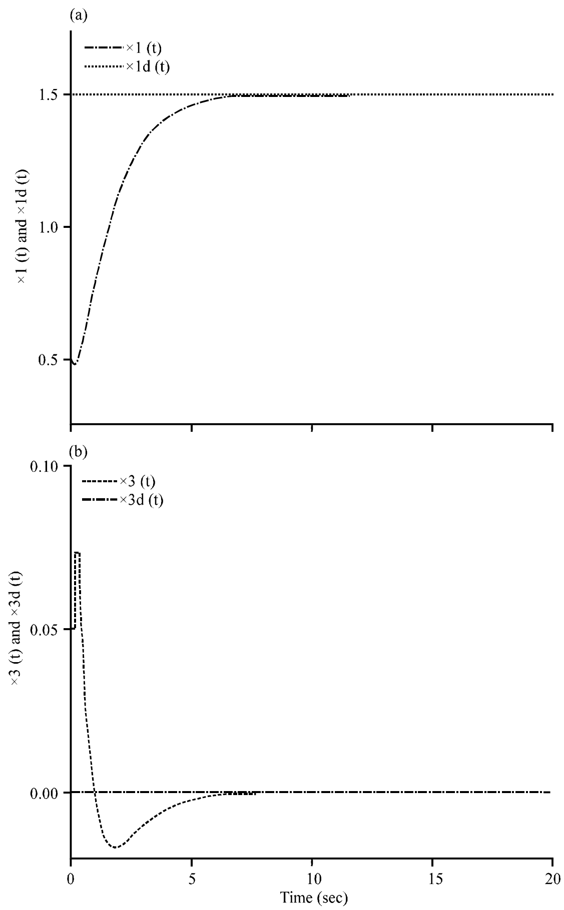

Fig. 2: a) Trolley position x(t) and b) Load angle θ(t)

$k_1 = 0.5$, $k_2 = 5$, $\beta_1 = 0.01$, $\beta_2 = 0.5$, $\sigma_1 = 1.5$, $\sigma_2 = 1.5$, T = 0.02. The desired position of the trolley x is: $x_{1d} = 1.5$ and the desired angle position θ is: $x_{3d} = 0$.

Figure 2 shows respectively the displacement of the trolley and the load, we see clearly that they can reach their equilibrium in finite time. A good precision and a stability performance are achieved.

Figure 3 shows the control input and the macro variables, we can see that the signal is very smooth. Figure 4 represents the comparison between the proposed controller (FTSynergetic) and the Fast Terminal Sliding Mode Controller (FTSMC) results.

We can see that the responses of the trolley and the load for the proposed controller are in finite time and faster than those obtained using (FTSMC).

In Fig. 5, the control signal is smooth with (FTSynergetic) while with (FTSMC) it contains the chattering. Therefore, the fast terminal synergetic controller is able to stabilising states with good precision in faster and finite time and without chattering.

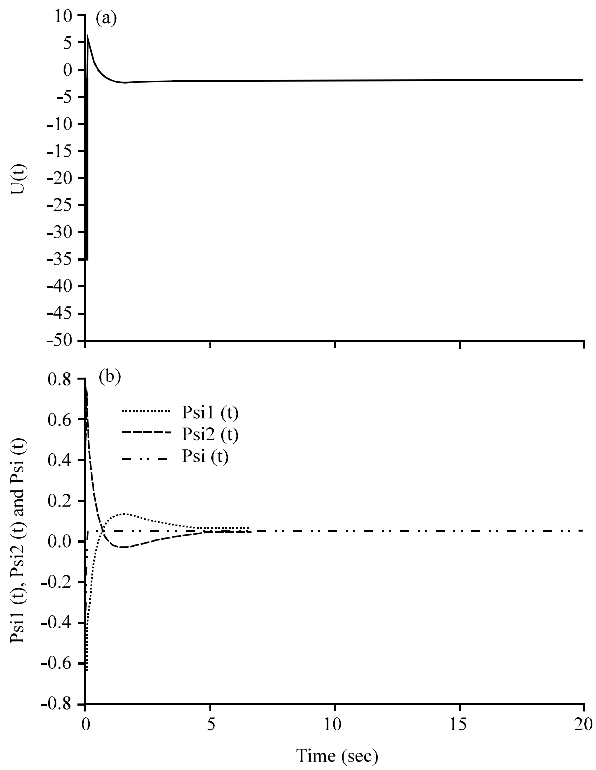

Fig. 3: a) The control signal and b) The macro-variables

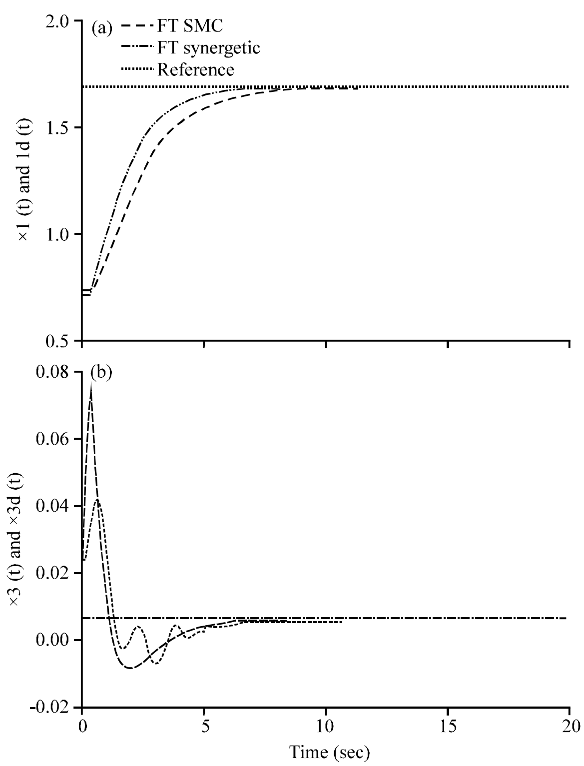

Fig. 4: a) Trolley positions comparison and b) Load angles comparison

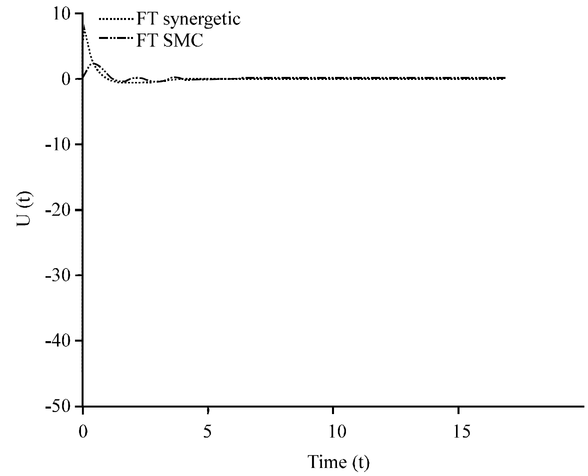

Fig. 5: The control signals comparaison

CONCLUSION

A fast terminal synergetic control for an overhead crane system has been presented in this study. This robust control gives a good precision and stability performance with faster and finite time response and without chattering phenomenon. The comparison with fast terminal sliding mode control in simulation results shows the effectiveness of the proposed controller. However, this methodology of control, leads the convergence to the equilibrium just in face of bounded uncertainties and perturbations where synergetic control tends to be more sensitive to differences between parameters in the model and in the physical system as future research, one can take into account this problem and give a solution using an observer or incorporating a fuzzy adaptive control.

REFERENCES

Chang, C.Y., 2007. Adpative fuzzy controller of the overhead cranes with non-linear disturbance. J. IEEE Trans. Ind. Informatics, 3: 164-172.

Hamalainen, J.J., A. Marttinen, L. Baharova and J. Virkkunen, 1995. Optimal path planning for a trolley crane: Fast and smooth transfer of load. IEE. Proc. Control Theory Appl., 142: 51-57.

Harmas, M.N., 2016. Synergetic control and synchronisation of chaotic systems. Intl. J. Control Autom. Commun. Syst., 1: 31-39.

Hong, K.S., B.J. Park and M.H. Lee, 2000. Two-stage control for container cranes. JSME. Intl. J. Ser. C Mech. Syst. Mach. Elem. Manuf., 43: 273-282.

Jiang, Z., 2007. Design of power system stabilizers using synergetic control theory. Proceedings of the IEEE Conference on Power Engineering Society General Meeting, June 24-28, 2007, IEEE, Tampa, Florida, USA., pp: 1-8.

Kolesnikov, A., G. Veselov and A. Kolesnikov, 2000. Modern applied control theory: Synergetic approach in control theory. TRTU., 1: 4477-4479.

Lee, H.H. and S.K. Cho, 2001. A new fuzzy-logic anti-swing control for industrial three-dimensional overhead cranes. Proceedings IEEE International Conference on Robotics and Automation ICRA01 Vol. 3, May 21-26, 2001, IEEE, Seoul, South Korea, pp: 2956-2961.

Liu, C.H. and M.Y. Hsiao, 2013. Synchronization on unified chaotic systems via PI-type terminal synergetic control. Proceedings of the 2013 CACS International on Automatic Control Conference (CACS), December 2-4, 2013, IEEE, Nantou, Taiwan, ISBN:978-1-4799-2383-0, pp: 24-29.

Liu, J. and X. Wang, 2012. Advanced Sliding Mode Control for Mechanical Systems: Design, Analysis and MATLAB Simulation. Springer, Berlin, Germany, ISBN:978-3-624-20907-9, Pages: 355.

Manson, G.A., 1992. Time-optimal control of and overhead crane model. Optimal Control Appl. Methods, 3: 115-120.

Nazemizadeh, M., 2013. A PID tuning method for tracking control of an underactuated gantry crane. Universal J. Eng. Mech., 1: 45-49.

Omar, H.M., 2003. Control of gantry and tower cranes. Ph.D. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Park, M.S., D. Chwa and S.K. Hong, 2008. Antisway tracking control of overhead cranes with system uncertainty and actuator non-linearity using an adaptive fuzzy sliding-mode control. IEEE Trans. Ind. Electron., 55: 3972-3984.

Qian, D., J. Yi and D. Zhao, 2011. Control of overhead crane systems by combining sliding mode with fuzzy regulator. IFAC. Proc. Vol., 44: 9320-9325.

Santi, E., A. Monti, D. Li, K. Proddutur and R.A. Dougal, 2003. Synergetic control for DC-DC boost converter: Implementation options. IEEE. Trans. Ind. Appl., 39: 1803-1813.

Shyu, K.K., C.L. Jen and L.J. Shang, 2005. Design of sliding-mode controller for anti-swing control of overhead cranes. Proceedings of the 31st Annual Conference on Industrial Electronics Society IECON05, November 6-10, 2005, IEEE, Raleigh, North Carolina, USA., pp: 147-152.

Singh, A.M., V.T. Hoang, and Q.P. Ha, 2016. Fast terminal sliding mode control for gantry cranes. Proceedings of the International Symposium on Automation and Robotics in Construction ISARC Vol. 33, January 1, 2016, Vilnius Gediminas Technical University, Vilnius, Lithuania, pp: 437-443.

Wang, W., X.D. Liu and J.Q. Yi, 2007. Structure design of two types of sliding-mode controllers for a class of under-actuated mechanical systems. IET. Control Theory Appl., 1: 163-172.

Yu, X. and M. Zhihong, 1998. Multi-input uncertain linear systems with terminal sliding-mode control. Automatica, 34: 389-392.

Zhai, S., Q. Chen and X. Tang, 2015. Finite-time synergetic control of mechanical system based on model-free friction compensation. Proceedings of the 2015 Conference on Chinese Intelligent Automation Conference, March 18, 2015, Springer, Berlin, Germany, ISBN:978-3-662-46462-5, pp: 275-284.