



## Backstepping Control Strategy for Overhead Crane System

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### KEY WORDS

Overhead crane, swinging, Backstepping control, Fuzzy Logic.

### ABSTRACT

*Swinging on the shifted load by overhead crane is one of the main problems that all researchers suffer from. In addition, the crane system is a nonlinear and under-actuated system. Furthermore it is multivariable problem and it has coupling between its parameters  $(x, \Theta)$ . In this work, a developed type of anti-sway Backstepping controller is proposed to solve swinging on the shifted load for full non-linear overhead crane system. Simulation results were validated against the related articles previously published which used Fuzzy Logic control. The enhancement is measured for Backstepping control as a swinging to achieve 50.7%, 38.1% and 42.5% when it is compared with Fuzzy Logic control. The performance of the overhead crane is enhanced from 70.4% to 51% at the control action consumptions.*

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## 1. INTRODUCTION

Overhead cranes are widely used in factories and ports because it has the capability of shifting loads with very high mass. As the crane system shifted a heavy load, swinging in the pendulum will occurred and this will make an accidents and dangerous situations to the workers in the field of the crane work.

The swaying in the load cause a low efficiency work and sometimes make a damage on the loads. Therefore; the overhead crane is required to high positioning accuracy, short transporting time, small sway angle and the safety. Furthermore, the overhead crane operation is hard work and several attempts were made to control load swing and trolley position [1].

Backstepping control is one of the most modern controllers employed to control nonlinear systems due to its ability to handle the nonlinearity and uncertainty with high efficiency. So there are many researchers who had suggested some strategies to controlling the overhead crane system. Mahfouf et al. [2] presented a Fuzzy Logic for controlling the crane system. The design procedure for Fuzzy Logic-based anti-sway is presented and the control system reaches the steady state so quick but with high swinging and high power consumptions. Solihin et al. [3] proposed a Fuzzy tuned PID to control the system. Fuzzy Logic is used as gain tuner to increase the robustness. A comparison between PID and Fuzzy tuned PID is occurred by using prototype system. They found that the PID controller is faster to reach the desired trolley displacement but with more singing than the Fuzzy tuned PID. Wahyudi et al. [4] presented a Fuzzy Logic with Nominal Characteristic Trajectory Following (NCTF) controller on the overhead crane system. Fuzzy logic is used as an anti-sway controller and NCTF controller for the position control. The design based on the open loop experiment and without modeling to the system. The proposed controller is compared with model-based PID and non-model based Fuzzy Logic and the result show that the proposed controller is more effective for each swinging and positioning. Smoczek et al. [5] used a Fuzzy logic and Pole Placement in order to control the overhead crane system. A stereovision used to determine the sway angle of the load. The results showed that the proposed control system can be implemented in manufacturing processes. Rong et al. [6] presented a three separate Fuzzy Logic based on Riccati discrete time transfer matrix method for controlling the system. The results show that the system is reaches the steady state rapidly but with undesirable swinging. Thirugnanam et al. [7] proposed positive zero-sway (PZS), positive zero sway- derivative (PZSD) and positive-zero-sway- derivative-derivative (PZVDD) are compared with PID control and apply it on the overhead crane system. They found that the input shaping control scheme is a better control scheme than the PID control. Finally, Kimmerle et al. [8] used Optimal Control for controlling the system. The design based on the ordinary differential equations to the system. The results showed that the system reaches the desired displacement slowly but with low swinging. Al-saedi introduced a design of feedforward and feedback controller to make the overhead crane move rapidly with small sway angle by adding a Fuzzy Logic to the controller for improving the system efficiency. Matlab Simulink is used to implement the model and the proposed controller. The results showed the effectiveness of the proposed controller, also showed that this controller has robustness of the parameters change [9].

It can be concluded from previous studies that the trolley was taken into the swaying problem and deal with it by different control strategies. Most of them used a prototype model with small parameter values. Also, the control systems which are used moved with high velocity and this causes a high swaying and high power consumptions due to the damage to the load and safety accidents. The problem in this system model is how to design a controller to reduce the swaying, reduces the power consumptions, and guarantee the stability of overall system.

This work suggests using the Backstepping control strategy to solve and address the swaying problem of the overhead crane. One of the significant issues that need to be taken into account is how to establish the state space representing the dynamic model of the swaying in the load for overhead crane that is suitable for Backstepping control design.

A Backstepping control algorithm is developed to solve the swaying problem of overhead crane system based on Regular Form based stability analysis. The aim is to guarantee asymptotic stability of swaying in the load controlled by Backstepping controller such that all errors finally converge to their corresponding equilibrium points.

## 2. MATHEMATICAL MODEL OF OVERHEAD CRANE

Figure 1 shows the overhead crane system model, including a two-dimensional trolley and pendulum combination, with presence of the load mass. X-axis and Y-axis is the trolley coordinate system which moves with the trolley. The trolley moves on the girder in the X-axis,  $\theta$  is the swing angle of the load in an arbitrary direction in space.

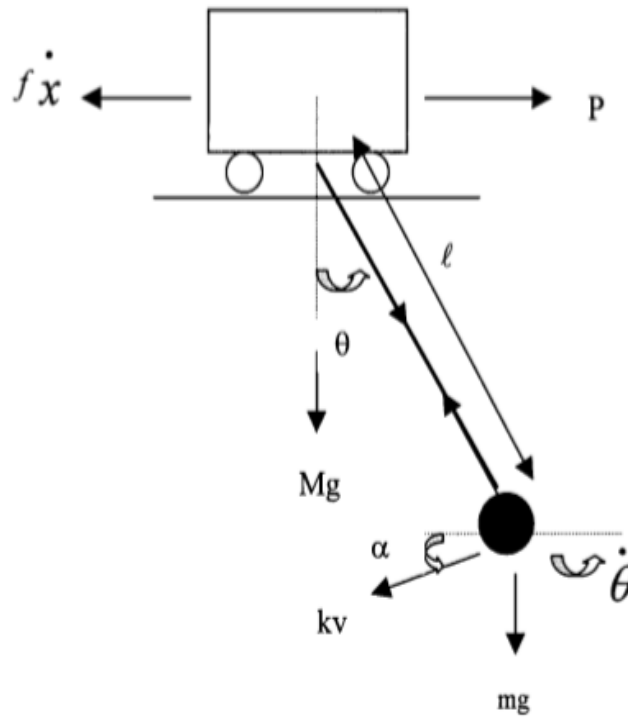


Figure 1: Schematic diagram of a simple crane [2].

The system model is derived below [2]:

Applying Newton’s second law for linear motion of trolley:

$$M\ddot{x} = P - f \cdot \dot{x} + T \cdot \sin \theta \quad (1)$$

Where P is the force in the trolley (N),  $\theta$  is the sway angle (rad), M is the trolley mass(Kg),  $\ddot{x}$  is the acceleration ( $m/sec^2$ ), f represents dynamics coefficient of friction ( $N \cdot sec/m$ ), T is the tension of the cable (N) and  $\dot{x}$  is the horizontal velocity (trolley velocity)( $m/sec$ ).

Applying Newton’s second law for angular motion of load:

$$\sum F = m \cdot \dot{\dot{x}} \quad (2)$$

Where  $\dot{\dot{x}}$  is the resultant acceleration.

$$-T \sin \theta - k \cdot v \cos \alpha = m \dot{\dot{x}} \quad (3)$$

Where m is the load mass(Kg), v represents the resultant of the air velocity( $m/sec$ ), k is the Coefficient of air resistant ( $N \cdot sec/m$ )

$$\dot{\dot{x}} = \ddot{x} + l\ddot{\theta} \sin \theta - l\dot{\theta}^2 \sin \theta \quad (4)$$

Where l represents the length of the cable (m) and  $\dot{\theta}$  is the angular velocity ( $rad/sec$ )

Subtitue Eq.(4) in Eq.(3) to get Eq.(5):

$$-T \sin \theta - k \cdot v \cos \alpha = m (\ddot{x} + l\ddot{\theta} \sin \theta - l\dot{\theta}^2 \sin \theta) \quad (5)$$

By adding Equ. (1) and Equ. (5) becomes:

$$(M + m) \ddot{x} = P - f \dot{x} - k \cdot v \cos \theta - m \cdot l\ddot{\theta} \cos \theta + m \cdot l\dot{\theta}^2 \sin \theta \quad (6)$$

Consider on the point mass m all forces will act:

$$\sum Torque = I \ddot{\theta} \quad (7)$$

I is the load inertia.

$$m \cdot l\ddot{\theta} = -m \cdot g \sin \theta - k \cdot v \cos(\theta - \alpha) - m \cdot \ddot{x} \cos \theta \quad (8)$$

Figure 2 shows the MATLAB-SIMULINK crane model representation by using Eqs. (6) and (8) and Figure 3 shows the subsystems of the crane model.

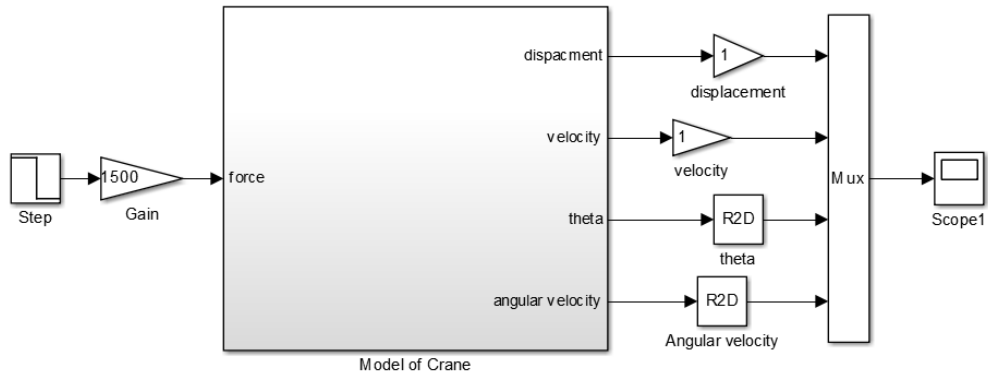


Figure 2: Open loop overhead crane system represented by MATLAB SIMULINK.

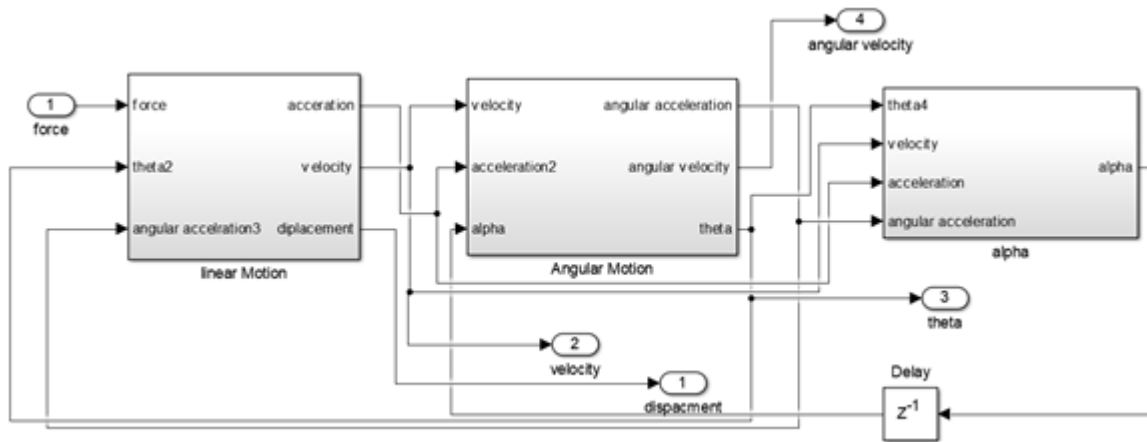


Figure 3: MATLAB SIMULINK for the model of the crane.

Figure 4.a represents the impulse input which used to drive the system and Figure 4.b shows the trolley displacement and its velocity in response to an impulse force input of 1500 N, including the load sway angle and its velocity. The purpose behind using the impulse input is the model has been bult for small intermittent duty time. The problem of overhead crane control will consist of moving the load to a predefined location while reducing the swaying angle in the minimum possible time. The main problem is the acceleration produced to satisfy the problem of position control, which will surely cause undesirable load swing which must be controlled in turn. The next section shows the configuration of the control.

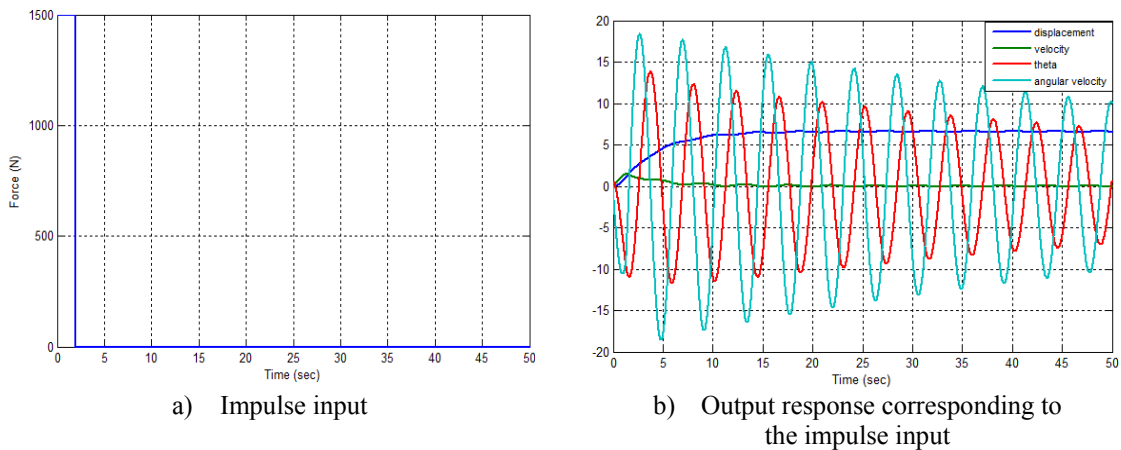


Figure 4: Open loop response of the overhead crane system.

### 3. CONTROLLER DESIGN

The problem of the overhead control is with three objectives: trolley positioning, anti-swinging load and reduce the power consumption. A type of Backstepping strategy will utilize to derive the control action equation. First a Regular Form will be used in this design, which is a mathematical transformation to the overhead crane dynamics  $(x, \theta)$  into new dynamics  $(y, z)$  as follows [10]:

$$z = \theta \quad (9)$$

$$\dot{z} = \dot{\theta} \quad (10)$$

$$y = f(x, \theta, \dot{x}, \dot{\theta}) \quad (11)$$

$$y = \tilde{x} + l * \ln(\sec(\theta) + \tan(\theta)) \quad (12)$$

$$\text{where } (\tilde{x} = x - x_d) \quad (13)$$

$x_d$  is the desired displacement (m).

The error equation is:

$$e = \theta - \tan^{-1}(c_1 \cdot \dot{y} + c_2 \cdot y) \quad (14)$$

where  $c_1$  and  $c_2$  are a positive numbers.

To make the control action ( $u$ ) appear in error equation, the above equation should be deriving two times:

$$\dot{e} = \dot{\theta} - \frac{c_1 \cdot \ddot{y} + c_2 \cdot \dot{y}}{(c_1 \cdot \dot{y} + c_2 \cdot y)^2 + 1} \quad (15)$$

$$\ddot{e} = \ddot{\theta} - \left[ \frac{c_1 \cdot \ddot{y} + c_2 \cdot \dot{y}}{(c_1 \cdot \dot{y} + c_2 \cdot y)^2 + 1} - \frac{2(c_1 \cdot \dot{y} + c_2 \cdot y)^2 (c_1 \cdot \ddot{y} + c_2 \cdot \dot{y})}{((c_1 \cdot \dot{y} + c_2 \cdot y)^2 + 1)^2} \right] \quad (16)$$

$$\ddot{\theta} = \frac{-\cos\theta}{l} k_1 k_u u - \frac{-\cos\theta}{l} k_1 k_2 \quad (17)$$

Substitute Eq. (17) into Eq. (16), this leads to Eq. (18):

$$\ddot{e} = \frac{-\cos\theta}{l} k_1 k_u u - \frac{-\cos\theta}{l} k_1 k_2 - \left[ \frac{c_1 \cdot \ddot{y} + c_2 \cdot \dot{y}}{(c_1 \cdot \dot{y} + c_2 \cdot y)^2 + 1} - \frac{2(c_1 \cdot \dot{y} + c_2 \cdot y)^2 (c_1 \cdot \ddot{y} + c_2 \cdot \dot{y})}{((c_1 \cdot \dot{y} + c_2 \cdot y)^2 + 1)^2} \right] \quad (18)$$

$$\ddot{e} = f(x) + G(\alpha)u = -w_1 e - w_2 \dot{e} \quad (19)$$

where  $w_1$  and  $w_2$  are positive numbers.

$$u = \frac{1}{G} (-f - w_1 e - w_2 \dot{e}) \quad (20)$$

$$\text{where } \frac{1}{G} = -\frac{l}{\cos\theta k_1 k_u} \quad (21)$$

$$f = \frac{-\cos\theta}{l} k_1 k_2 + \left[ \frac{c_1 \cdot \ddot{y} + c_2 \cdot \dot{y}}{(c_1 \cdot \dot{y} + c_2 \cdot y)^2 + 1} - \frac{2(c_1 \cdot \dot{y} + c_2 \cdot y)^2 (c_1 \cdot \ddot{y} + c_2 \cdot \dot{y})}{((c_1 \cdot \dot{y} + c_2 \cdot y)^2 + 1)^2} \right] \quad (22)$$

$$k_1 = 1/m \sin^2\theta + M \quad (23)$$

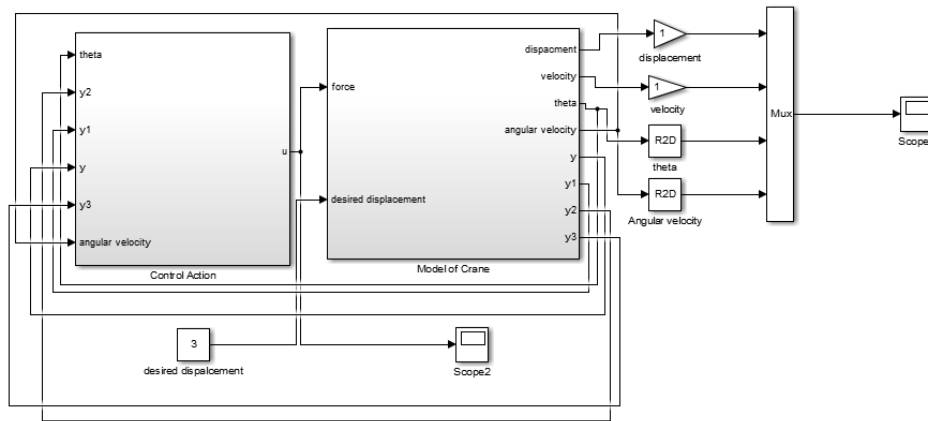
$$k_2 = \frac{M+m}{m l \cos\theta} (g \sin\theta) + m \dot{\theta}^2 \sin\theta \quad (24)$$

$k_u$  is DC motor constant = 1500 N/volt

So, the control action equation becomes:

$$u = -\frac{l}{\cos\theta k_1 k_u} \left[ \frac{-\cos\theta}{l} k_1 k_2 + \frac{c_1 \cdot \ddot{y} + c_2 \cdot \dot{y}}{(c_1 \cdot \dot{y} + c_2 \cdot y)^2 + 1} - \frac{2(c_1 \cdot \dot{y} + c_2 \cdot y)^2 (c_1 \cdot \ddot{y} + c_2 \cdot \dot{y})}{((c_1 \cdot \dot{y} + c_2 \cdot y)^2 + 1)^2} \right] - w_1 (\theta - \tan^{-1}(c_1 \cdot \dot{y} + c_2 \cdot y)) - w_2 \left( \dot{\theta} - \frac{c_1 \cdot \ddot{y} + c_2 \cdot \dot{y}}{(c_1 \cdot \dot{y} + c_2 \cdot y)^2 + 1} \right) \quad (25)$$

The control action equation is connected with the crane system model in MATLAB SIMULINK named (Control Action) as in Figure 5.



**Figure 5: MATLAB SIMULINK of the overhead crane control system.**

The desired displacement ( $x_d$ ) is applied to Eq. (12), so, the trolley will move as much as desired so the results of the system have been discussed in the next section. Figure (6) represents the MATLAB/SIMULINK of the control action subsystem, Eq. (25).

**4. SIMULATION AND RESULTS**

The controller is assessed and the performance of Backstepping controlled system is discussed via simulation using MATLAB/SIMULINK environment. The values of system parameters of the overhead crane are listed in Table I [1, 5]. At first the position and sway angle to the trolley are (0,0), and the control objective is to make the trolley carry the load safely to the desired displacement with minimum swaying.

**TABLE 1: Physical Parameters of the overhead crane [1, 5]**

Load mass (Kg)	Trolley mass (Kg)	Rope length (m)
250	1000	5
1000	1000	5
10	30	3

These parameters are used in the model with the Backstepping controlled system. The results are compared with Mahfouf et al. [1] and Rong et al. [5]. An uncertainty with  $\pm 20\%$  is applied to the load mass ( $m$ ) and friction ( $f$ ) because with time the parameters values will be changed slightly or the system suffering from external disturbances such as air resistance and friction [11]. This percentage of the uncertainty is our case study.

The control action behavior in Figure 7 is the same with and without uncertainties with controller parameters which found by try and error ( $w_1=100$ ,  $w_2= 20$ ,  $c_1=0.1$  and  $c_2 =0.15$ ). In Figure 8 when adding 20% of uncertainty in parameters is applied, the system becomes slower and had smaller angular velocity (swaying) than decreasing 20% of uncertainty in parameters. These results have less swaying than the results shown in [1] by about 50.7% to the swaying and by about 70.4% for control action consumption as shown in Table II.

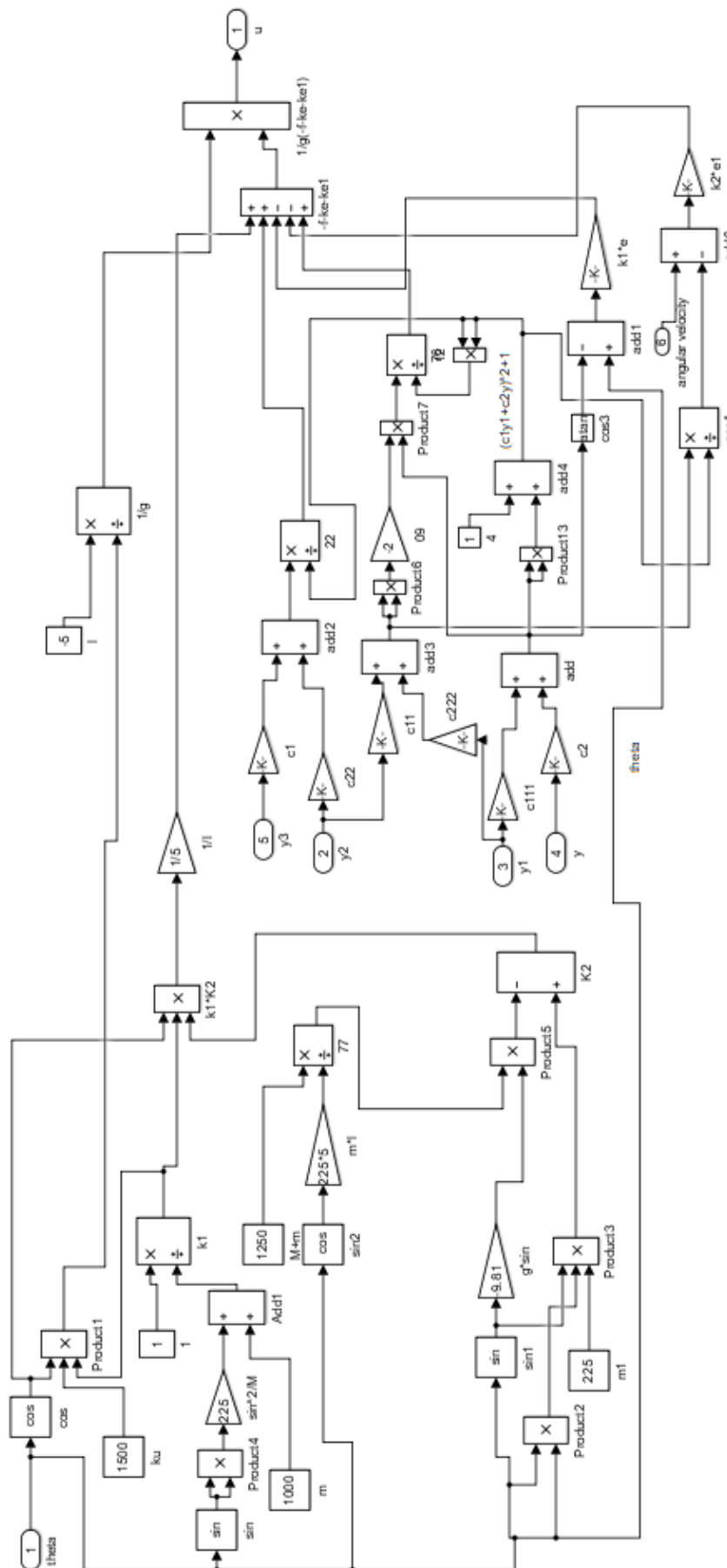


Figure :6 MATLAB SIMULINK of the Control Action (u) equation.

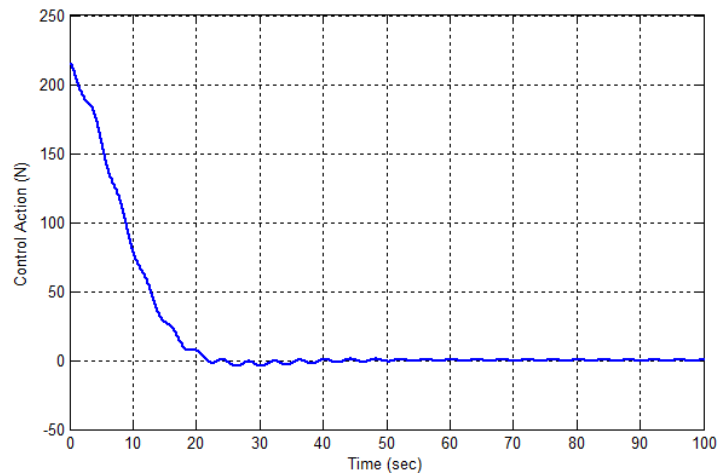
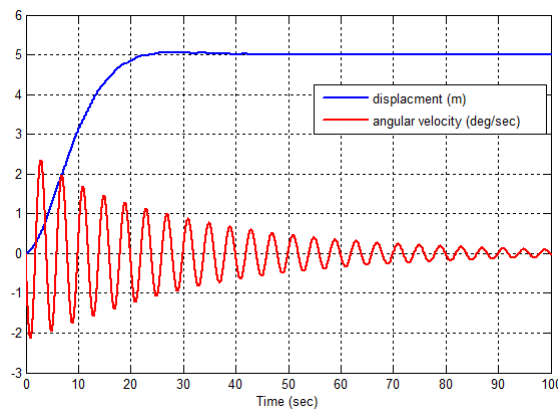
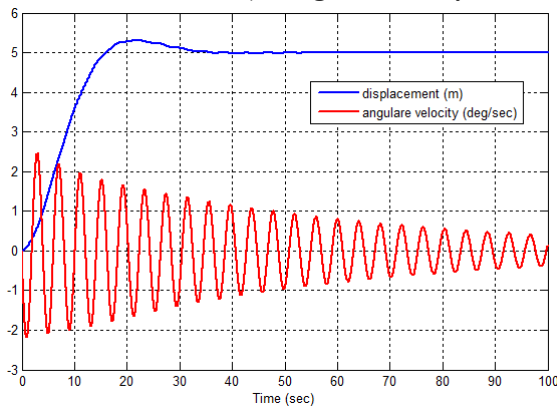


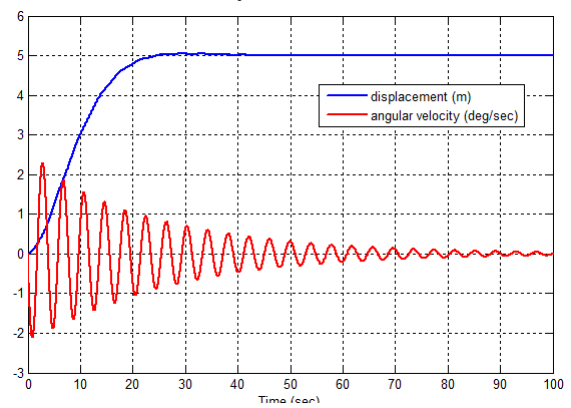
Figure 7: Control Action for the nominal and disturbed controlled system for load mass 250Kg and desired displacement 5m.



a) Angular velocity and displacement to the nominal system.



b) Angular velocity and displacement with -20 % uncertainty.



c) Angular velocity and displacement with +20% uncertainty

Figure 8: Comparison between angular velocity and displacement for the nominal and disturbed Backstepping controlled system with load mass 250Kg and desired displacement 5m.

TABLE II: Comparison between Fuzzy Logic controller and Backstepping controller for nominal system case.

Max. angular velocity (deg./s)			Power consumption (N)		
Fuzzy Logic	Backtepping	Improvement ratio	Fuzzy Logic	Backtepping	Improvement ratio
-4.3	-2.17	49.5%	750	222	70.4%
+5.2	+2.56	50.7%			

The control action behavior in Figure 9 is the same with and without uncertainties with controller parameters found by try and error ( $w_1=81$ ,  $w_2= 18$ ,  $c_1=0.1$  and  $c_2 =0.5$ ). In Figure 10, For +20%



uncertainty case, this make the system reach the steady state with longer time than when the system with -20% uncertainty but with low smaller swaying. It is clear that when the load mass being heavy, the angular velocity becomes smaller. These results have less swaying than the result shown in [1] by about 30% to the swaying and by about 50% control action consumption. The angular velocity fluctuation when the load mass 1000kg is less than when the load mass is 500kg, as in the previous case, because the control system now carry a heavy load so the system is slightly affected by disturbances and uncertainties. Furthermore the control system becomes slow to reach the steady state but with low swinging and less power consumption as shown in Table III.

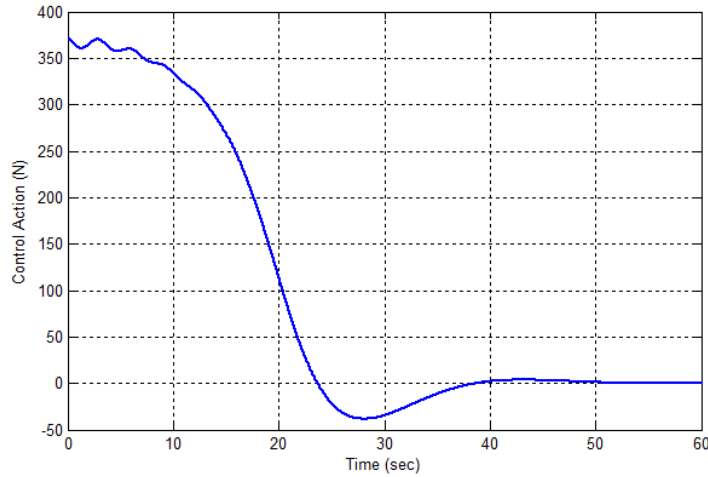
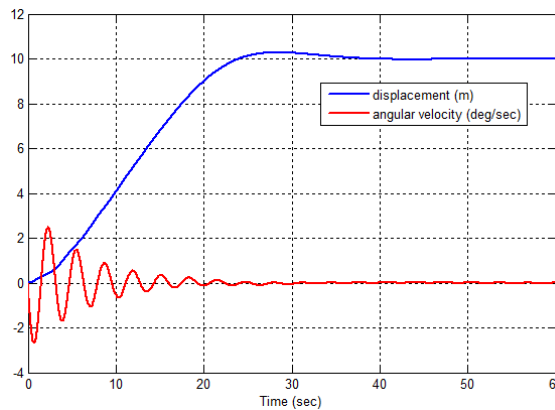
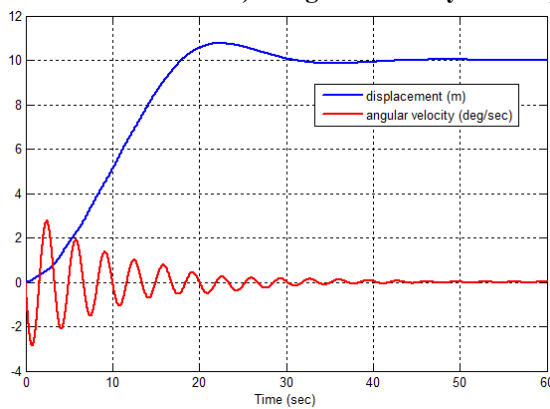


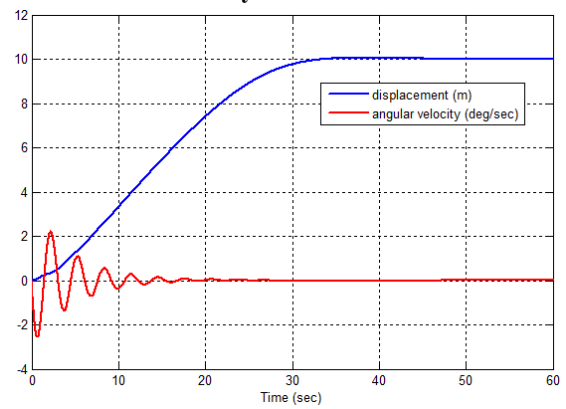
Figure 9: Control Action for the nominal and disturbed controlled system for load mass 1000Kg and desired displacement 10m.



a) Angular velocity and displacement to the nominal system.



b) Angular velocity and displacement with -20 % uncertainty.



c) Angular velocity and displacement with +20% uncertainty

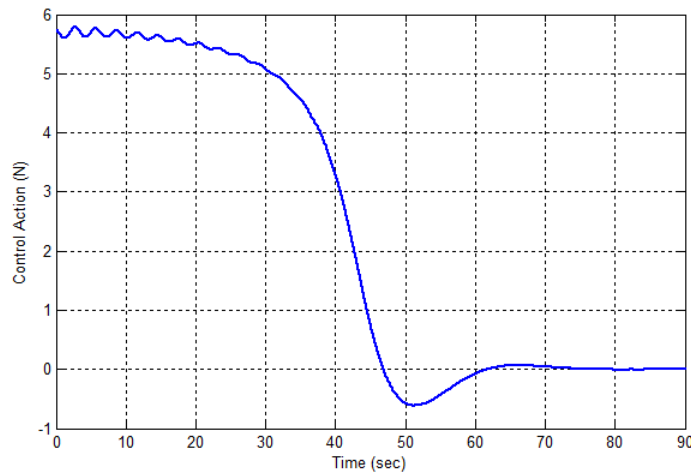
Figure 10: Comparison between angular velocity and displacement for the nominal and disturbed Backstepping controlled system with uncertainties with load mass 1000Kg and desired displacement 10m.

**TABLE III: Comparison between Fuzzy Logic controller and Backstepping controller for nominal system case**

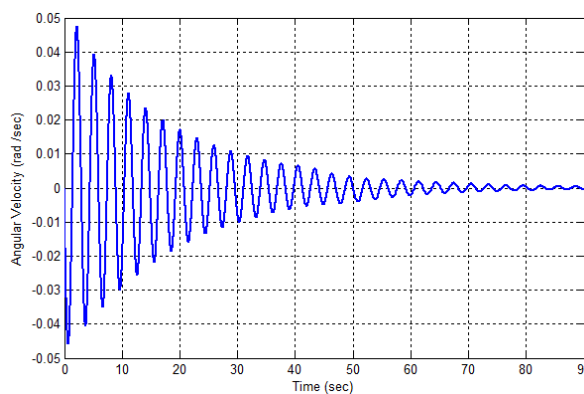
Max. angular velocity (deg./s)			Power consumption (N)		
Fuzzy Logic	Backtepping	Improvement ratio	Fuzzy Logic	Backtepping	Improvement ratio
-3.4	-2.76	18.8%	750	367	51%
+3.75	+2.32	38.1%			

The control action behavior in Figure 11 is the same with and without uncertainties with controller parameters found by try and error ( $w_1=64$ ,  $w_2= 16$ ,  $c_1=0.01$  and  $c_2 =0.7$ ). In Figures 12 and 13 when the +20% uncertainty is applied, the system becomes slower to reach the desired displacement and had smaller angular velocity (swaying) than -20% uncertainty. These results have less swaying than in [5] by 35% to the swaying. In this case the mass of the load and the trolley is so small, therefore; the control system becomes so sensitive to any disturbances and uncertainties. This explains why the angular velocity is so fluctuated when the -20% uncertainty was applied.

It is clear that the system with +20% uncertainty is slower than the -20% uncertainty because the mass of the load and the friction is increased by 20%, so the system swinging becomes smaller when the mass become larger. Even with the uncertainty, the control system still stable and had smaller swaying as compared with the related papers. Table IV shows Comparison between Fuzzy Logic controller and Backstepping controller.



**Figure 11 Control Action for the nominal and disturbed controlled system for load mass 10Kg and desired displacement 18m.**



**a) Angular velocity to the nominal system.**

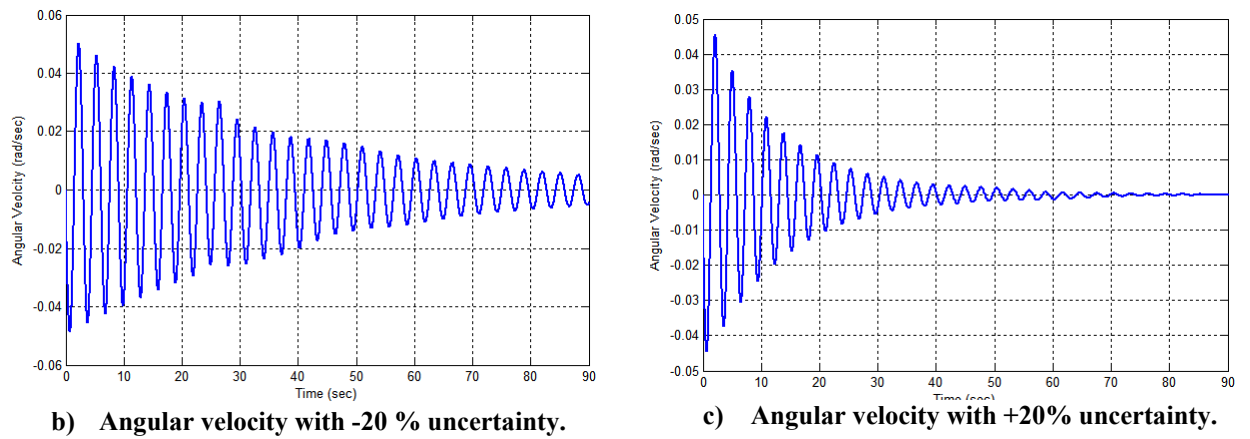


Figure 12: Comparison between angular velocity for the nominal and disturbed Backstepping controlled system with uncertainties with load mass 10Kg and desired displacement 18m.

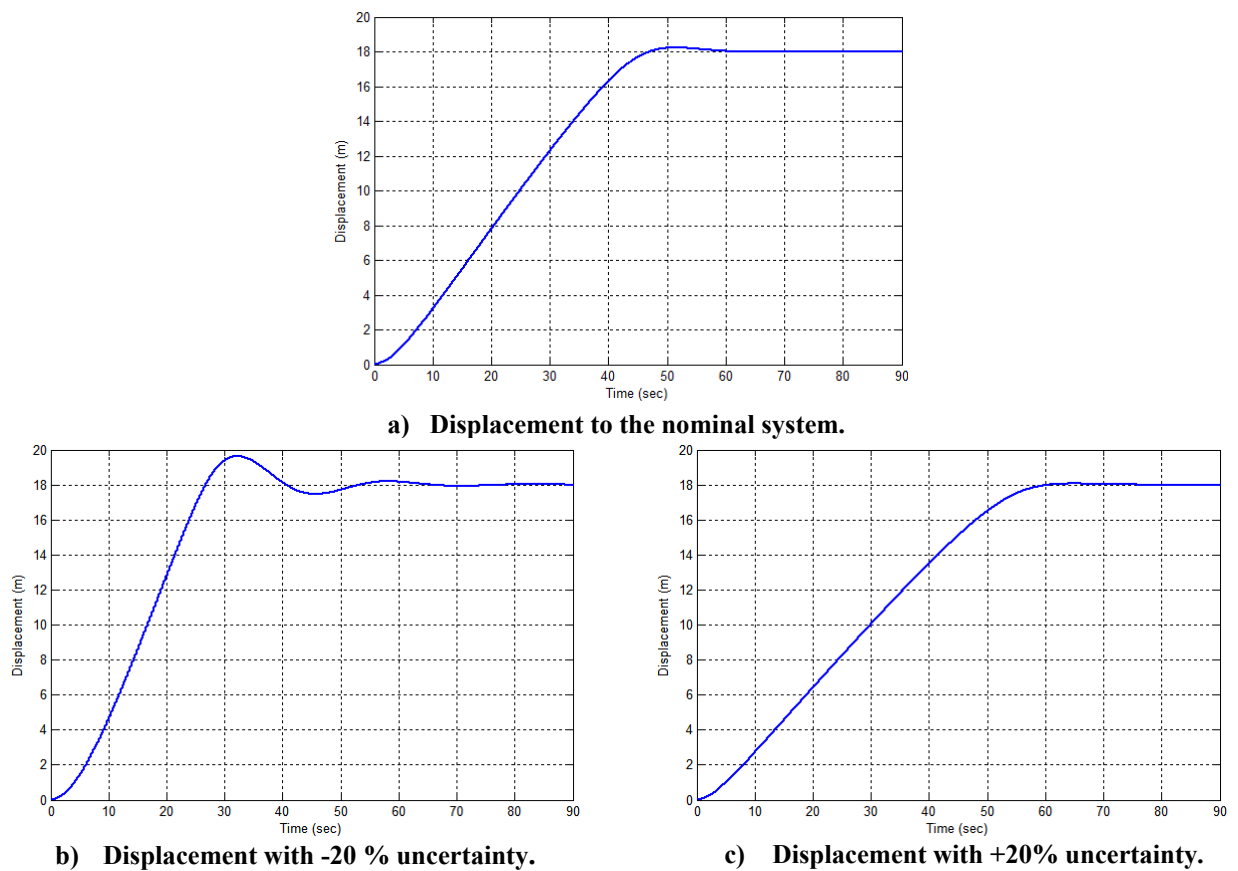


Figure 13: Comparison between displacement for the nominal and disturbed Backstepping controlled system with uncertainties with load mass 10Kg and desired displacement 18m.

TABLE IV: Comparison between Fuzzy Logic controller and Backstepping controller for nominal system case

Max. angular velocity (rad./s)		
Fuzzy Logic	Backtepping	Improvement ratio
-0.08	-0.046	42.5%
+0.075	+0.048	36%

## 5. CONCLUSIONS

The crane system is a nonlinear and under-actuated system. It has coupling between its dynamics  $(x, \theta)$  and it is a multi-variable problem. A regular form has used to derive the control action equation. The objective of the controller is to make the desired output  $(y)$  equals to zero this leads to that  $\tilde{x} = 0$  i.e.  $x_d = x$  and with minimum possible swaying. The proposed Backstepping controller results showed that the swaying is decreased by 50.7%, 38.1% and 42.5%. Also, an improvement in the control action consumptions was obtained from 70.4% to 51% when compared with the previous studies.

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