Fuzzy-logic based Anti-Sway Control Design For Overhead Cranes

M. Mahfouf[*] , C. H. Kee, M.F. Abbod and D. A. Linkens

Department of Automatic Control and Systems Engineering
The University of Sheffield, Mappin Street,
Sheffield S1 3JD
The United Kingdom

[*] *Corresponding Author*

Email: M.Mahfouf@Sheffield.ac.uk
Tel: +44 (0) 114 222 5607
Fax: +44 (0) 114 273 1729

ABSTRACT

A non-linear model for an overhead crane system is derived which takes into account a combination of a trolley and a pendulum. The overall mathematical model hence obtained is simulated using MATLAB-SIMULINK. Open-loop simulations run on cases depending on whether the air resistance is taken into account or not and whether the angle of oscillation is small or large indicate the validity of such model, hence reflecting similar trends in industries which are concerned with material handling equipment. A hand crafted fuzzy controller, which includes two rule-bases, one for position control, the other one for sway-angle control, was designed and successfully implemented on the above simulated model. Preliminary results are very encouraging and indicate the feasibility of such a two-rule-base control strategy. The results obtained are presented, analysed and discussed.

KEYWORDS

Fuzzy logic, crane control, modelling, rule-base, non-linear.

INTRODUCTION

Overhead cranes have the potential of handling loads of hundreds of tonnes and are widely used in railway depots, offshore platforms, ships, factories and dockyards. The time taken to transport loads from one point to another and also to unload them is of the essence, where each hour gained represents an important money saving operation.

For years, industries concerned with handling equipment design and manufacturing have been concentrating on problems of load sway. Indeed, the design of a system that has the ability to minimise load sway and consequently allow faster goods off-loading will bring many rewards to such industries which will be able to save time and hence costs as the volume of loaded and unloaded goods increases.

Humans, who are usually extensively trained on all aspects relating to a particular crane-model, manage the majority of crane control operations. It is however, worth noting that the major problem that can be identified with crane operation is the desire to position the load in the wanted area, without acceleration of the crane itself causing undesirable swings, which in some cases can damage the goods and can even cause serious accidents. However, as the volume of loaded and unloaded goods in dockyards, for instance, increases, and the constraints on time become even tighter, technologies surrounding the design and the manufacturing of these cranes is becoming more and more complex and thus difficult for humans to manage their operations with similar ease and effectiveness as they used to do.

Therefore, emphasis has therefore recently shifted towards designing anti-sway control systems able to combine speed and precision in such operations. This control is not easy as it combines all challenges only too familiar to control engineers, i.e. the crane problem is non-linear, multivariable, and dominated by uncertainties. Various researchers reported applications of open-loop optimal control (Mita and Kanai, 1979), closed-loop LQG (Benhidjeb and Gessinger, 1993) which they later compared to a fuzzy control strategy (Benhidjeb and Gessinger, 1995). The target positions were shorter that one would expect in an industrial environment. An anti-sway control system combining a position control with a PD-controller was proposed by Lee *et al* (1997) but considered only small angle sways of up to 4 degrees, although one should expect angles of up to 45 degrees, especially in offshore platforms and in windy conditions.

This paper proposes a new method for the design of an anti-sway control system based on the theory of fuzzy logic with a reduced number of rules than what appeared before in the literature. A non-linear model based on a trolley and a pendulum was used for this purpose. Various cases, relating to the air-resistance, angle of oscillations as well as the various masses involved are considered for model reduction and will be outlined in the next sections.

MATHEMATICAL MODELLING OF OVERHEAD CRANES

The overhead crane system is modelled as a combination of a trolley and a pendulum as shown in Figure 1:

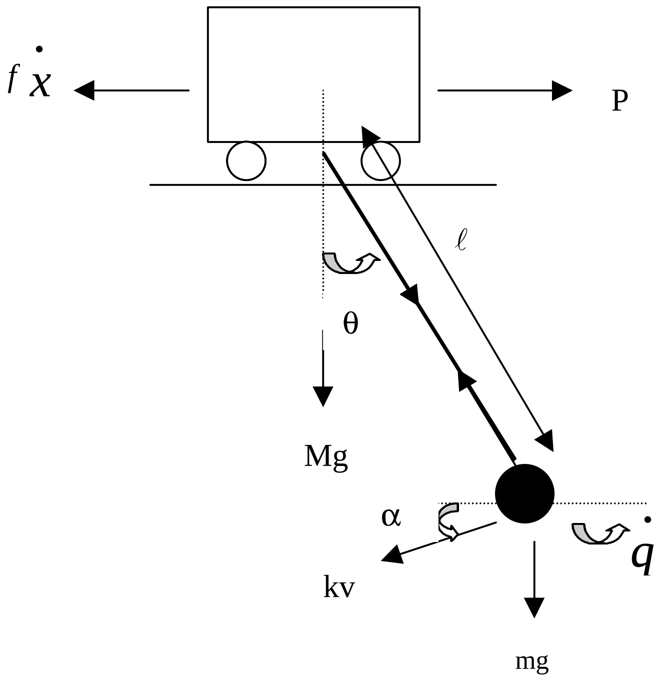


Figure 1 Schematic Diagram of A Simple Crane

Where,

P =Applied force (N)

f =Friction coefficient on trolley (Ns/m)
T = Tension of string (N)
k = Coefficient of air resistant (Ns/m)
v = Resultant velocity of the point mass m (m/s)
M = Trolley mass (kg)
ℓ = Length of the string (m)
m = load mass (kg)
$\dot{q}$ = Angular velocity of the point mass (rad/s)
$\dot{x}$ = velocity of the trolley (m/s)

First, Consider the trolley having a mass *M*. One can write:

$$P - f.\dot{x} + T\sin q = M.\ddot{x} \tag{1}$$

Consider the forces acting on the mass *m* on the pendulum. One can write:

$$\sum F = m.\ddot{x}' \tag{2}$$

where $\ddot{x}'$ is the resultant acceleration of the point mass *m*.

or,

$$-T\sin q - k.v.\cos a = m\ddot{x}' \tag{3}$$

Because the resultant horizontal acceleration of the point-mass *m* can be written as follows:

$$\ddot{x}' = \ddot{x} + l\ddot{q}\cos q - l\dot{q}^2\sin q \tag{4}$$

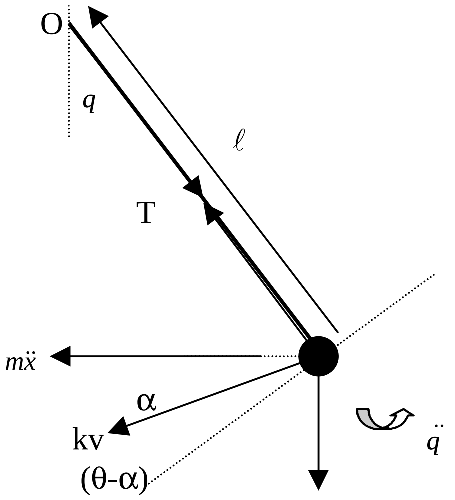
Equation (3) becomes:

$$-T\sin q - k.v.\cos a = m(\ddot{x} + l\ddot{q}\cos q - l\dot{q}^2\sin q) \tag{5}$$

Using Equation (1), equation (5) becomes:

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

Consider all the reaction forces acting on the point mass *m* as shown in Figure 2; one can write:



mg

Figure 2 Reaction Forces acting on the point mass m

$$\sum Torque = I\ddot{q} \qquad (7)$$

where *I* is the moment of inertia. Hence, by taking the moment of momentum about the fixed point *O*, one can write:

$$m.l\ddot{q} = -m.g.\sin q - k.v.\cos(q - a) - m.\ddot{x}\cos q \qquad (8)$$

Hence, Equations (6) and (8) are representative of the dynamics relating to the overhead crane of Figure 1. Simulation of the model using MATLAB-SIMULINK can be done using those equations with the following assumptions:

- Load m can be considered as a point mass *m*.
- The cable mass is negligible compared to the load.
- When the crane is in motion, the length *l* is considered to be constant.

Figure 3 shows the MATLAB-SIMULINK representation of the crane system according to the dynamics of Equations (6) and (8).

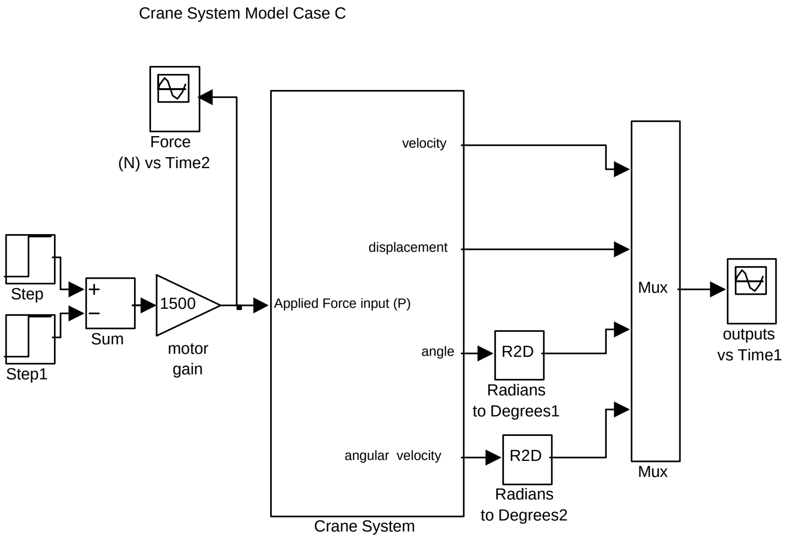


Figure 3 MATLAB-SIMULINK diagram of the dynamics relating
To the overhead crane system of Figure 1.

Using the above configuration an open-loop study was conducted using the following parameters:

Crane head/trolley mass, *M = 1000kg;*
Load mass, *m = 100kg;*
Cable length, ℓ *= 5m;*
Friction coefficient, *f = 0.3 * (M+m) Ns/m;*
Gravity, *g = 9.81m/s/s;*
Air resistant coefficient, *k = 0.05.*

In the following simulations and throughout, it is assumed that a DC-motor drives the trolley and is considered to be linear and has a constant of 1500.

Figure 4a shows the trolley displacement, its velocity together with the load sway angle and its velocity, in response to an impulse force input of *1500 Newtons* as shown in Figure 4b. Therefore, The crane control problem will consist of taking the load to a predefined position while minimising its sway-angle in the minimum amount of time possible. The major problem being the acceleration generated to satisfy the position control problem, which will inevitably induce unwanted load swing, which in turn must be controlled. The next section explains the control design, which will allow achievement of these objectives.

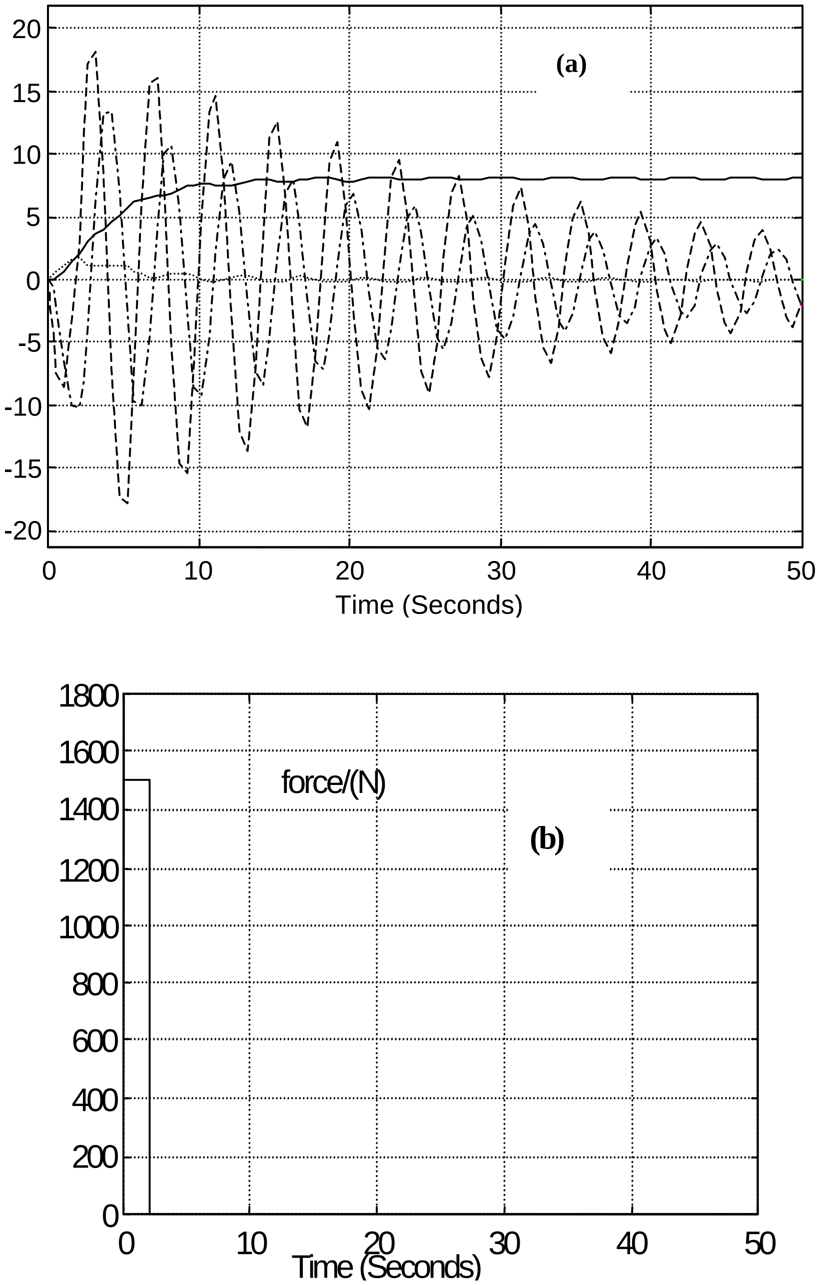


Figure 4 Open-loop response of the crane system represented by Figure 1.

(a) Output response: continuous line: trolley displacement;
Dotted line: trolley velocity; dashed: load sway angle;
Dash dotted line: load angle velocity.

(b) Impulse force input.

CONTROLLER DESIGN

As already mentioned, several controllers have been designed in the past ranging from simple PID controllers to LQG controllers. In this research study and due to uncertainties surrounding the system, a fuzzy logic –based controller is designed. Furthermore, recent emphasis in fuzzy logic control has focused on formulating rule-bases with a reasonable number of fuzzy rules (Mahfouf and Linkens, 1998), hence placing more weight on quality of the rules rather on the quantity of the same rules; this is in contrast to rule-bases which include more than 25 rules at a time. Taking into account this and exploiting the Fuzzy Logic MATLAB Toolbox, two rule-bases were hand-crafted; one for position control which included 25 rules and the other one for sway angle control which included only 5 rules. Consistency is the only property which was not possible to satisfy, for we wanted the controller to act abruptly against inertia. For position control, the two inputs were trolley error displacement and its change of error velocity, and the output was the force. Five fuzzy labels, Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB) were used with Gaussian Membership functions. For Sway angle control, the two inputs were trolley error displacement and sway angle velocity, whereas the output was the force. Tables 1 and 2 display the fuzzy rules.

		e_x				
		NB	NS	Z	PS	PB
$\dot{x}$	NB	NB	PS	PB	PB	PB
	NS	NB	Z	PS	PS	PB
	Z	NB	NS	Z	PS	PB
	PS	NB	NS	NS	Z	PB
	PB	NB	NB	NB	NS	PB

Table 1 Fuzzy rule-base for position control.

		x
		Z
$\dot{q}$	NB	NB
	NS	NS
	Z	Z
	PS	PS
	PB	PB

Table 2 Rule-base for sway angle control.

Figure 5 represents the MATLAB-SIMULINK block diagram of the overall crane control system.

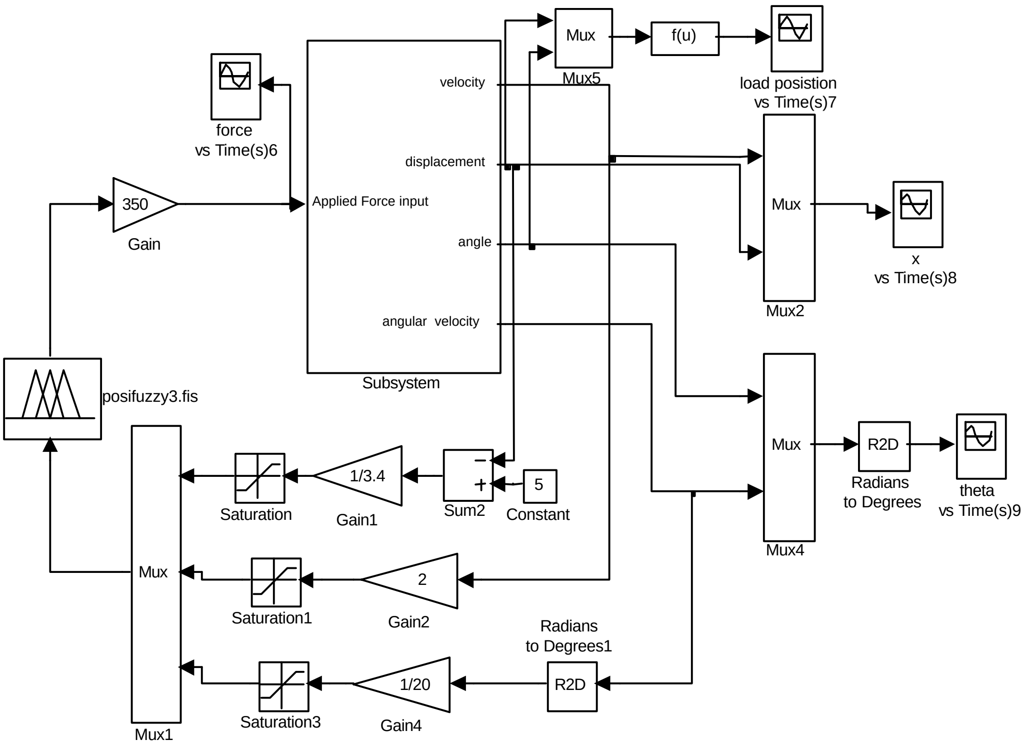


Figure 5 MATLAB-SIMULINK implementation of the two-fuzzy rule-base anti-sway crane control system.

At this stage it is worth noting that the control strategy consists of firing the rules relating to position control first, i.e. Table 1 and once the required displacement has been achieved, sway control represented by the fuzzy rules of Table 2 are fired accordingly. In turn, Figures 6a, b display the control surfaces relating to the two rule-bases. The figures show the non-linear aspecct of the rules with a flat enough area around the equilibrium point.

SIMULATION RESULTS

In order to validate the fuzzy control strategy designed above a series of simulation experiments were carried-out. Load masses and target displacements of up to 1000 *Kg* and 30 *m* were considered for this evaluation respectively. Figure 7 shows the result of a run conducted using a load mass of 250 *Kg* and a target displacement of 5 *m*. As can be seen from Figure 7a, the trolley took around 8 seconds to reach the 5 *m* target whereas the sway angle of Figure 7b was reduced to 0 in just under 10 seconds which can be considered to a good performance for this magnitude of displacement. The input force, shown in Figure 7d, shows a reasonable control activity. For a heavier load of 1000 *Kg* and a longer target displacement of 10 *m*, the results of the run are shown in Figure 8. It can be seen that the trolley took longer to reach the target with a sway-angle converging to 0 only after 15 seconds approximately (see Figure 8b). Figure 8d shows the controller’s output which was reasonably active.

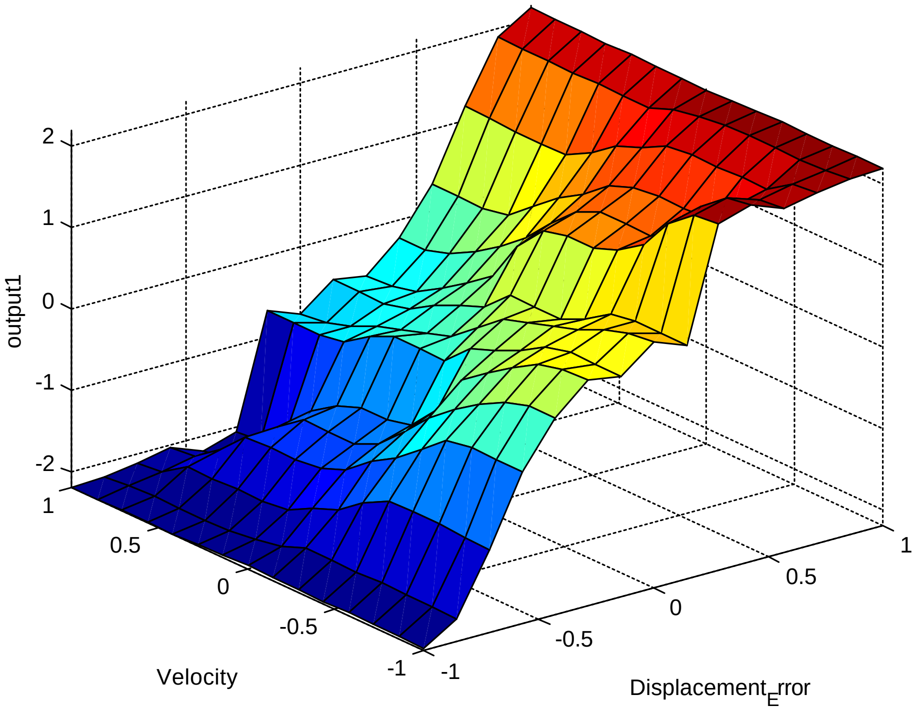


Figure 6a Control surface relating to the fuzzy rule-base of *Table 1*

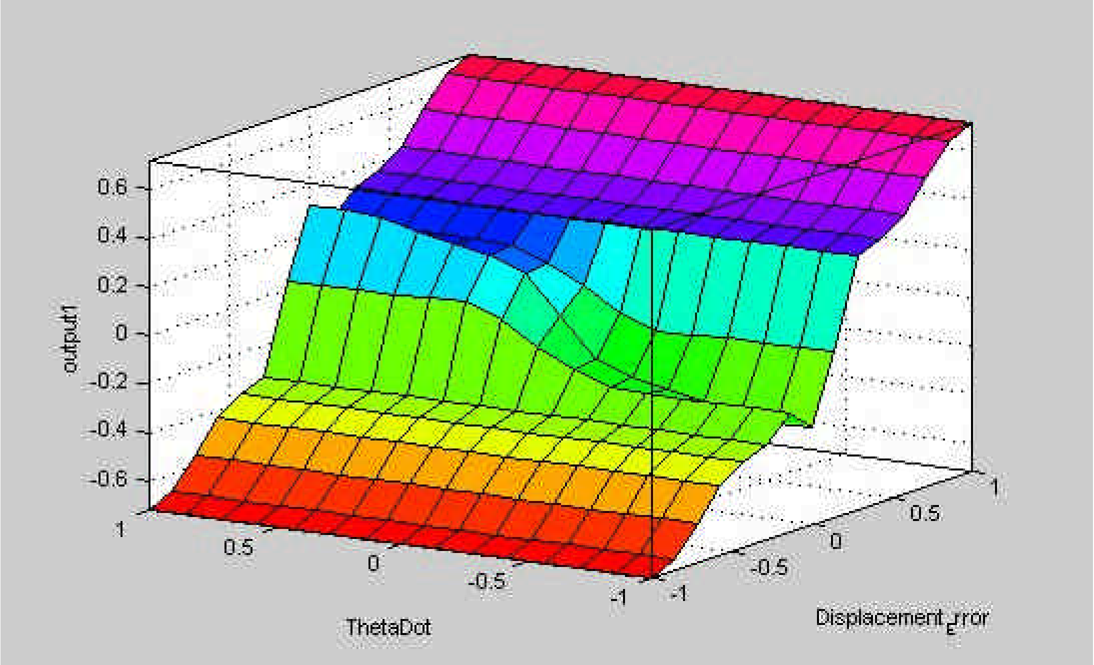
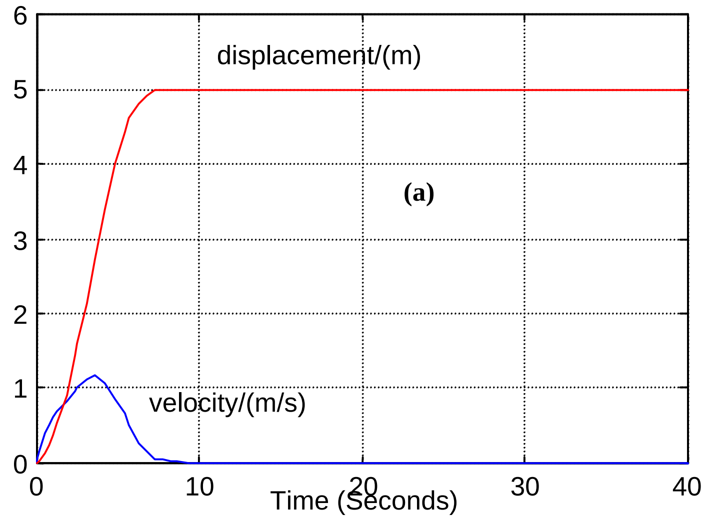
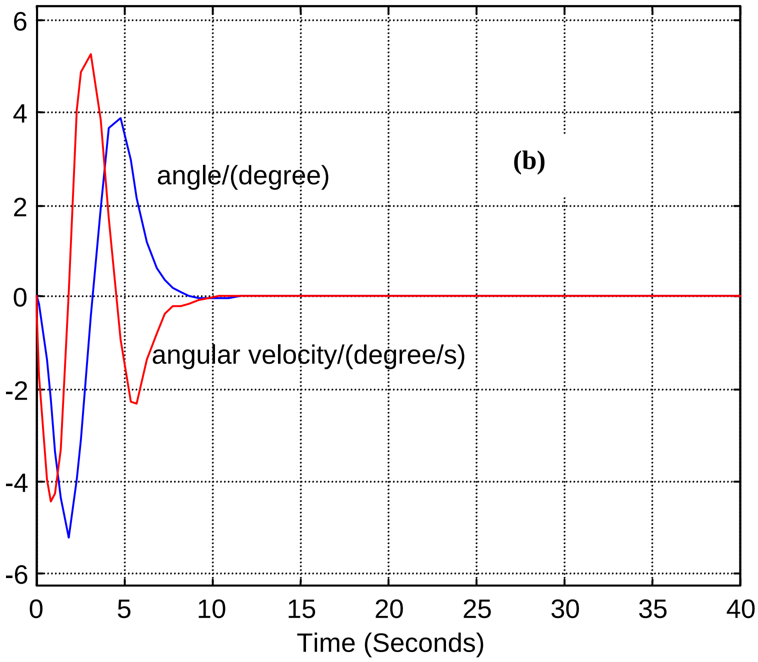


Figure 6b Control surface relating to the fuzzy rule-base of *Table 2*


6
5
4
3
2
1
0
0
10
20
30
40
Time (Seconds)
displacement/(m)
(a)
velocity/(m/s)


6
4
2
0
-2
-4
-6
0
5
10
15
20
25
30
35
40
Time (Seconds)
angle/(degree)
(b)
angular velocity/(degree/s)

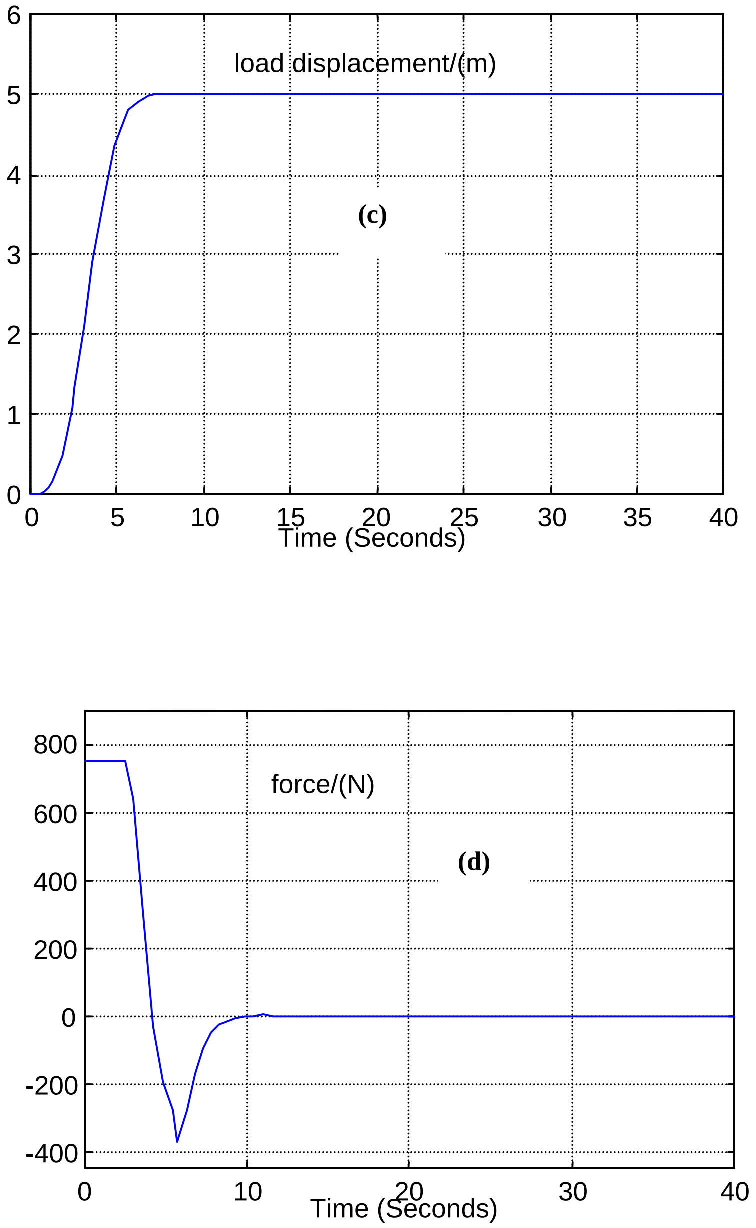
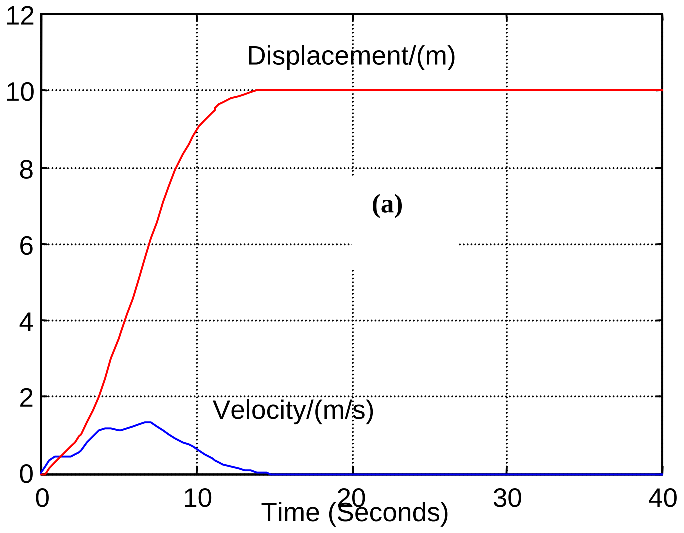
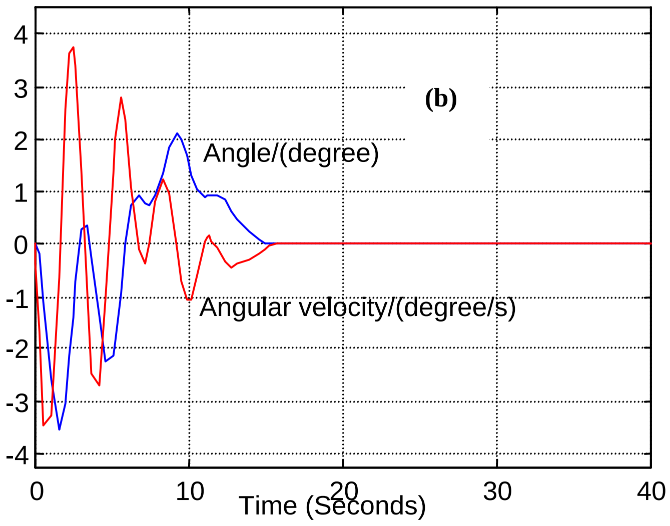


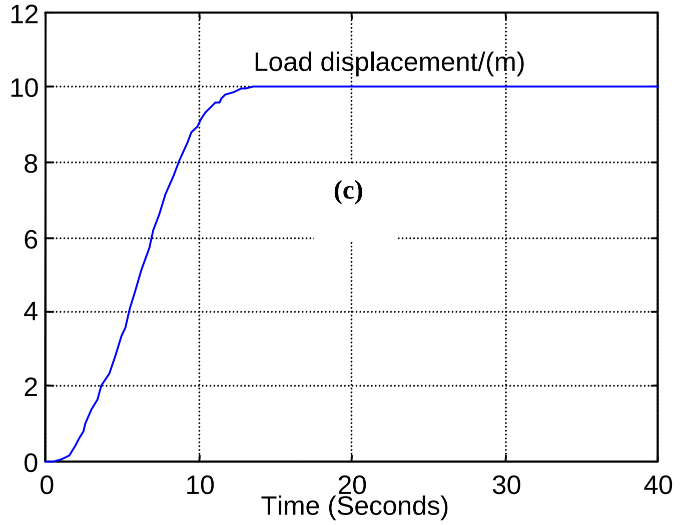
Figure 7 Fuzzy logic control of overhead cranes for a load mass of 250 *Kg* and a target displacement of 5 *m*:

(a) Trolley displacement; (b) sway angle and its velocity;

(c) Load displacement; (d) Control input (force).


Displacement/(m)
(a)
Velocity/(m/s)
12
10
8
6
4
2
0
0
10
20
30
40
Time (Seconds)


(b)
Angle/(degree)
Angular velocity/(degree/s)
4
3
2
1
0
-1
-2
-3
-4
0
10
20
30
40
Time (Seconds)



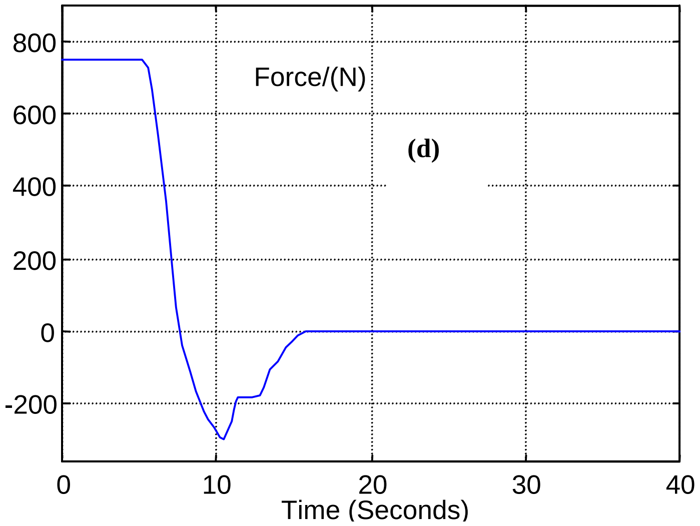


Figure 8 Fuzzy logic control of overhead cranes for a load mass of 1000 *Kg* and a target displacement of 10 *m*:

(b) Trolley displacement; (b) sway angle and its velocity;

(c) Load displacement; (d) Control input (force).

CONCLUSIONS

A fuzzy logic controller with two rule-bases is proposed for ant-sway control for overhead cranes. It is widely recognised that the crane system dynamics are complex and are characterised by the too well-known challenges facing control engineers, such as nonlinearities and uncertainties. In this study we proposed a non-linear model of the crane which is by no means all complete, but it includes as much information to conduct an extensive control analysis, which in this case was based on fuzzy logic. In fact, fuzzy logic, which can do away with a model, has already been applied in real-time to control one type of cranes used within Rolls-Royce Industries (Mahfouf *et al*, 1997). In this study, the fuzzy logic controller included two rule-bases; one for position control, the other one for sway angle control. Both rule-bases were hand-crafted with a reasonable amount of fuzzy rules. The study showed that the controller can perform well within a relatively wide range of crane parameters relating to load mass and target displacements. It is hoped to improve the controller to include adaptation inherently within the system by using a Self-Organising Fuzzy Logic Control (SOFLC) scheme for instance.

REFERENCES

Benhidjeb and G.L. Gissinger, *Fuzzy control of an overhead crane- performance comparison with classic control,* Control Eng. Practice, **3**, No. 12, pp 1687-1696, 1995.

Benhidjeb and G.L. Gissinger, *Commande Automatique d’un pont roulant; validation temps reel des algorithmes,* J.T.E.A., HAMMAMET, TUNISIE, **1,** pp 195-199, 1993.

Ho-Hoon Lee, Sung-Kun Cho, Jae-Sung Cho , *A New Anti-Swing Control Of Overhead Cranes,*The Proc. Of ASI’97 pp137-142, July 16-18,1997.

Mahfouf, M. and D.A. Linkens, *Generalised predictive Control and Bioengineering,* Taylor and Francis Publishers, ISBN 0-74884-0597-6, 1998.

Mahfouf, M., B. Mitchell and C. Morgan, , Unpublished Report, Dept. of Mechanical Engineering, The University of Manchester, 1997.

Mita, K. and Kanai, T., *Optimal control of the crane system using maximum speed of the trolley,* Trans. Soc. Instrum. Control Eng., **15**, No. 6, pp 833-838, 1979.