Anti-Swing Fuzzy Controller Applied in a 3D Crane System

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***Abstract*—It is well known that fuzzy logic can be used in the control of complex systems described by highly nonlinear mathematical models. However, the main difficulty in the design of a fuzzy controller comes with the adjustment of the controller's parameters that are usually determined by human experts' knowledge or trial and error methods. In this paper, we describe an implementation of fuzzy logic in order to reduce oscillations during the positioning of a 3D crane system. The fuzzy controller's structure is quite simple, requiring only two input variables. The proposed fuzzy controller has been applied to an experimental laboratory framework and results show that oscillations are significantly reduced.**

Keywords- fuzzy controller; anti-swing control; 3D crane system

I. INTRODUCTION

The crane system is an electromechanical system, which is used to lift and lower some materials and to move them from one place to another. It is mainly used for lifting heavy things and moving loads beyond the normal capability of a man. There are several types of crane systems, but in our interest is in the 3D crane system, where the payload attached to the end of the lift-line can move freely in three dimensions. The 3D crane mathematical model is rather complicated, and it is often simplified in some way.

The exact mathematical models for crane systems are very important for controller design. Many attempts were made to introduce simplified models or to use some control techniques to cope with system uncertainness. In [1], several 3D crane mathematical models, depending on the number of variables, are described. The authors gave (*i*) a complete nonlinear model with constant pendulum length and two control forces, (*ii*) a complete nonlinear model with varying pendulum length and three control forces, and (*iii*) a simplified model with tree control forces. On the other hand, when the friction and gravity are unknown, neural networks (NNs) can be used [2]. NNs are used for approximation of the whole nonlinearity of robot dynamics, but they can be adjusted for 3D crane system. Moreover, the authors in [3] propose an adaptive PD control with gravity compensation for the case where parameters in gravitational torque vector are unknown. It is well-known that some control techniques do not require an exactly known mathematical model of the controlled plant. Having in mind this, the robust methods are seemed to be the right choice in the control of 3D crane system.

The main objective in the control of 3D crane system is to position the payload in the desired location without oscillations. There are many papers dealing with this control problem. In [4], boundary conditions are used in the time optimal control. In [5], the authors improve the previous paper and the optimal control is calculated so that the corresponding trajectory satisfies the specified boundary conditions and the oscillations during the transfer are minimized. However, some requirements of time optimization must be neglected if we want to increase robustness. In [6], it is proposed to use zero angular velocity at the target point. Gain scheduling, in order to increase tracking accuracy, is proposed in [7]. Authors in [8], interpreted the crane as a large workspace serving robot, and developed several observers.

Intelligent control algorithms, such as fuzzy, sliding mode, neural, genetics etc., have a lot of advantages related to the interpolative reasoning approach, but also have some restrictions due to their complexity. In [9], authors investigate the intelligent control algorithms (PID, fuzzy) applied in 3D crane model control. In [10], a network-based self-tuning controller is presented, based on using a multilayer perceptron, as a self-tuner for the controller. The given method is verified by simulations in different conditions. The implementation of genetic algorithms in determining parameters of a 3D crane system model is given in [11]. The validation of the model and parameters are performed by digital simulation and comparison with the experimental results. The method proposed had satisfactory control performance under a wide range of operating conditions and reduced oscillations during the positioning of payload cart. A sliding mode anti-swing control for overhead cranes is proposed in [12]. The proposed control realizes a typical anti-swing trajectory control, allowing high-speed load hoisting motion and sufficient damping of load swing. In [13], a new fuzzy anti-swing control scheme for a three-dimensional overhead crane is proposed. The proposed control consists of a position servo control and a fuzzy logic control. The validation of the proposed control is done by experiments with a three-dimensional prototype overhead crane.

As we mentioned before the main control goal is to reduce the swing of the payload while moving it to the desired position as fast as possible. However, the swing of the payload depends on the acceleration of the trolley, so minimizing the operation time and minimizing the payload swing are partially conflicting requirements. Having this in mind, one particular method for limiting vibration in flexible systems by shaping the input to the system is presented in [14]. As difference to the most previous input shaping strategies, this method does not require a precise system model or lengthy numerical computation. In [15], the author proposes one method for a high performance anti-swing control of overhead cranes, where the motion planning problem is solved as a kinematic problem. In [16], the authors developed a nonlinear model for an overhead crane and then that model is used for anti-swing control development. The feedback control is used to specify the crane speed at every moment. In [17], a nonlinear tracking controller with two loops (outer and inner), is designed. Loops are used to stabilize the internal oscillatory dynamics.

Similar to the most of the previously described papers, in this paper we developed an anti-swing control method in order to reduce the oscillations during the positioning of a 3D crane system. The difference between the desired and actual position and the derivative of that difference are used as the input variables for the fuzzy controller. The main advantage of this controller is that its structure is quite simple in comparison to some other structures mentioned above.

The paper is organized as follows. Section II starts with the description of the 3D crane experimental framework used for the validation of the proposed control algorithm, and continues with the mathematical model of the 3D crane system. The controller design is presented in section III. In Section IV, the proposed control method is applied to the crane system and experimental results are discussed. Concluding remarks are given in Section V.

II. 3D CRANE SYSTEM

A. Laboratory Experimental Framework Description

Practical 3D crane framework, used in experiments performed in this paper, is presented in Figure 1 [1]. This framework, made by Inteco, is placed in the laboratory of Control Systems in Faculty of Electronic Engineering, Nis, Serbia. 3D crane represents a nonlinear electromechanical system having a complex dynamic behavior and creating challenging control problems.

The 3D crane system consists of a payload hanging on a pendulum-like lift-line wound by a motor mounted on a cart. The payload attached to the end of the lift-line can move freely in three dimensions: in x direction (both the rail and the cart can move horizontal), in y direction (the cart can move horizontal along the rail) and in z direction (the payload is lifted and lowered in this direction).

Fig. 1. 3D Crane System made by Inteco.

There is one DC motor, at the end of each axis. Furthermore, there are five identical measuring encoders measuring five state variables: the cart coordinates on the horizontal plane (used for controller design), the lift-line length (in our case used as constant), and two deviation angles of the payload. The encoders measure movements with a high resolution equal to 4096 pulses per rotation. The deviation of the load is measured with a high accuracy equal to 0.0015 rad. The power interface amplifies the control signals which are transmitted from the PC to the dc motors. It also converts the encoders pulse signals to the digital 16-bit number. The PC equipped with the RT-DAC/PCI multipurpose digital I/O board communicates with the power interface board. The whole logic necessary to activate and read the encoder signals and to generate the appropriate sequence of pulses of pulse width modulation (PWM) to control the dc motors is configured in the Xilinx chip of the RT-DAC/PCI board. All functions of the board are accessed from the 3D crane toolbox which operates directly in the MATLAB® /Simulink® environment.

The user has rapid access to all basic functions of the 3D crane control system from the Main Control Window in MATLAB. It includes tests, drivers, models and application examples. The main driver is located in the RTWT Device Driver column. The driver is a software go-between for the real crane MATLAB environment and the RT-DAC/PCI acquisition board. The driver has three PWM inputs (dc motor controls) for the X, Y and Z axes. There are eight outputs of the driver: X position, Y position, Z position, two angles and additionally three safety switches. According to a preprogrammed logic the internal XILINX program of the RT-DAC/PCI board can use the switches to stop the DC motors.

B. 3D Crane Mathematical Model

Graphical representation of the 3D crane system is depicted in Figure 2. Despite the model simplification, it preserves the fundamental characteristics of the real system. The forces acting on this system and relevant variables, needed for the model development, are presented. An important element in the construction of the mathematical model is the appropriate choice of the system of coordinates. Despite the fact that the

Cartesian system is simple in interpretation, it is not convenient for the description of the rotational motion dynamics, so we choose the spherical system. As we can see from Figure 2, the position of the payload is described by two angles α and β. The shortcoming of the spherical system of coordinates is that for every point on the y-axis, the corresponding value of β is not uniquely determined. However, this is not valid in the case of the real crane systems, so it can be neglected. The position of the payload is described by the following equations:

$$x_c = x_w + R\cos\alpha\ , \tag{1}$$

$$y_c = y_w + R\sin\alpha\sin\beta\ , \tag{2}$$

$$z_c = -R\sin\alpha\cos\beta\ , \tag{3}$$

where x_w represents the distance of the rail with the cart from the center of the construction frame, and y_w is the distance of the cart from the center of the rail. The parameters of the 3D crane model are given in the Table I.

In similar manner, the dynamics of the crane can be obtained as:

$$m_c\ddot{x}_c = -S_x\ , \tag{4}$$

$$m_c\ddot{x}_c = -S_y\ , \tag{5}$$

$$m_c\ddot{x}_c = -S_z - m_c g\ , \tag{6}$$

$$m_w\ddot{x}_w = F_x - T_x + S_x\ , \tag{7}$$

$$\left(m_w + m_s\right)\ddot{x}_w = F_y - T_y + S_y\ , \tag{8}$$

where S_x, S_y and S_z are the components of the vector S.

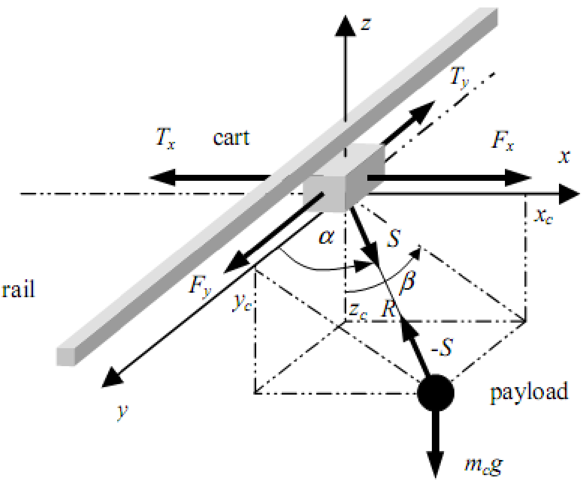

Fig. 2. 3D crane system: coordinates and forces.

TABLE I. PARAMETERS OF 3D CRANE MODEL

Symbol	*Description*
R	length of the lift-line
α	angle between the y-axis and the lift line
β	angle between the negative direction on the z-axis and the projection of the lift line onto the xz plane
m_c	mass of the payload
m_w	mass of the cart
m_s	mass of the moving rail
x_c, y_c, z_c	coordinates of the payload
S	reaction force in the lift-line acting on the cart
F_x	force driving the rail with cart
F_y	force driving the cart along the rail
T_x, T_y	friction forces

$$S_x = S\cos\alpha\ , \tag{9}$$

$$S_y = S\sin\alpha\sin\beta\ , \tag{10}$$

$$S_z = -S\sin\alpha\cos\beta\ . \tag{11}$$

The mathematical model of 3D crane system is completely determined by these equations. This model is used as the controlled plant for the controller design, presented in the next Section.

III. CONTROLER DESIGN

In [18], we considered the implementation of genetic algorithms in the determination of the parameters of PI controllers. In this section we propose an anti swing fuzzy controller, which gives better results compared to [18]. A control structure, based on fuzzy controllers, is developed for the previously described experimental framework. The main fuzzy controller's structure is shown in Figure 3. As it can be seen, it consists of three processes: fuzzification, fuzzy concluding, based on fuzzy rules, and deffuzification.

Let us define the error for x position of the payload as:

$$e_x = x_{cdes} - x_c \tag{12}$$

where the x_{cdes} represents desired and the x_c is actual, x position of the payload, respectively.

Differentiating (12) results in:

$$\dot{e}_x = \frac{d}{dt}\left(e_x\right) = \frac{d}{dt}\left(x_{cdes} - x_c\right) \tag{13}$$

In a similar manner, the error e_y and the error first derivative $\dot{e}_y$ for the y position of the payload can be defined. These four variables are used as inputs for the two anti-swing controllers, one for the x position and one for the y position of the payload, as shown in Figure 4.

The coordinate z_c of the payload is considered to be a constant. The controller outputs are named u_x and u_y, and they represent the PWM inputs (DC motor controls) for the x- and y-axis, respectively.

Each of the associated fuzzy variables for e, $\dot{e}$ and u has seven linguistic terms. This terms are described by equally distributed Gaussian membership functions for e and $\dot{e}$ and triangular ones for u. We choose a qualitative category for each of them as NL (negative large), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium) and PL (positive large). The rule base for the anti-swing controller is presented in Table II, and it has the same form for x- and y-axis, so we give only one. As a defuzzification method according to the control problem specificity, the center of gravity (COG) method was chosen.

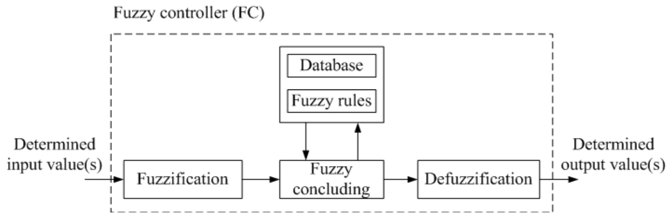

Fig. 3. Standard structure of fuzzy controller.

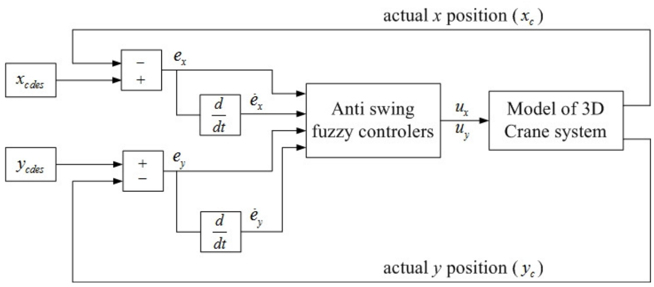

Fig. 4. Simulation block diagram of the 3D crane control.

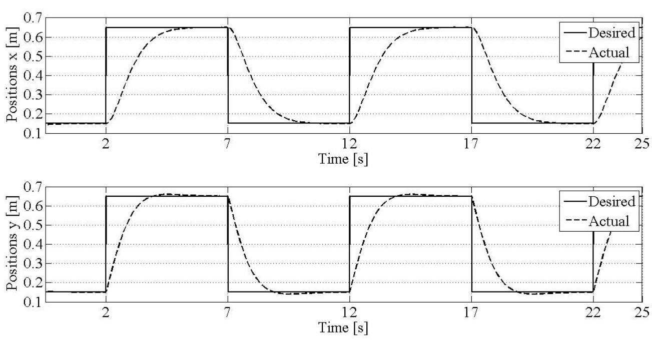

Fig. 5. Experimental results for x and y positions.

TABLE II. ANTI-SWING FUZZY CONTROLLER RULE BASE

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

IV. EXPERIMENTAL RESULTS

Practical verification of the proposed anti-swing fuzzy controller is performed on the experimental 3D crane setup presented in Figure 1. As mentioned earlier, this is the experimental environment in which the users verify their 3D control algorithms in real time using MATLAB and Simulink toolboxes. The experimental results of the 3D crane with the proposed anti-swing fuzzy controller are compared with the results obtained by the implementation of a PI controller [18].

The square wave is used as a reference signal. This type of signal matches the real situation, where the cart with payload is driven from the home position to the desired position and back to the home position. The square signal has amplitude of 0.8m and frequency of 0.1Hz. It is assumed that the crane starts from home position (x_c, y_c)=(0, 0). Experimental time was set to 25s. The results of the payload positions after using anti-swing fuzzy controllers are shown in Figure 5. It is shown that the proposed control algorithm gives quite better results in comparison to those in [18]. However, due to oscillations, actual y position slightly exceeds the desired position. On the other hand, it tracks desired position quite well.

V. CONCLUSION

This paper deals with the problem of reducing oscillations during the positioning of the payload. The 3D crane system is described by a nonlinear model, so using some robust methods in the control seems to be the right choice. In this paper, we present an anti-swing fuzzy controller for 3D crane positioning. The difference between desired and actual position and the first derivative of that difference are used as inputs for the controller. The short description of experimental framework and its mathematical model are given first, and then, experimental setup is employed for the practical verification of the proposed control algorithm. Results show that the method described in the paper shows good system accuracy.

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