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FUZZY LOGIC-BASED CONTROL OF THREE-DIMENSIONAL CRANE SYSTEM*

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Abstract. *The control of three-dimensional (3D) crane system represents one of the most widely challenging control problems. 3D crane system is used for lifting and moving loads horizontally, as well as lowering and realizing the gripper to the original position. In this paper fuzzy logic-based control of three-dimensional crane (3D) system is presented. Hence the system produces oscillations during moving loads, the main objective of the designed controller is to control the swing angle. As a plant for controller design, the bond graph model of 3D crane system is used. To verify the effectiveness of the proposed control method, several digital simulations with concrete values of parameters are performed using Matlab. The simulations results show that the proposed fuzzy logic control produce better performance in regard to the reduction of undesired oscillations.*

Key words: *bond graph, 3D crane, Dymola, fuzzy control, modeling and simulation, Matlab/Simulink*

1. INTRODUCTION

The concept of bond graphs was first developed by Paynter [1]. The main idea was further developed by Karnopp and Rosenberg [2, 3]. The fundamental advantage of bond graphs is in central physics concept-energy (bond graph consists of components which

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exchange energy using connections; these connectors represent bonds). The effort (voltage, force, pressure, etc.) and the flow (current, velocity, volume, flow rate, etc.) are generalizations of similar phenomena in physics. The factors which characterize the effort and flow have different interpretations in different physical domains (mechanical, electrical, hydraulic, thermal, chemical systems). The obtained model can be successfully tested in the software package *Dymola* which is adjusted for simulation purposes.

Dymola is a commercial modelling and simulation environment based on the open *Modelica* modelling language (an object-oriented, declarative, multi-domain modelling language for component-oriented modelling of complex systems). The *BondLib* library, firstly presented by *Cellier* in 2003, is designed as a graphical library for modelling physical systems using the bond graph metaphor. This library contains the basic elements for analog electronic circuits, translational and rotational mechanical systems, hydraulic and thermal systems.

It is already proven in many papers that bond graph technique can be successfully used as a modeling tool for various types of process [4-10]. In [11, 12] we used bond graph method for modeling of submersible pumps in water industry. The obtained model is used as an object for the control design based on orthogonal polynomials. In [13] we presented the process of modelling and simulation of three-dimensional laboratory model of industrial crane. In addition, the simulation of the obtained model is performed using *Dymola* and simulation results are compared with the already existing one and it is proved that this model fully describes the 3D industrial crane system dynamics.

Intelligent control algorithms, 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 [14-16]. In [15] we presented an anti-swing fuzzy controller for 3D crane positioning. In [17], network-based self-tuning controller, based on using a multilayer perceptron is presented.

In this paper, we go one step further and we design controller based on fuzzy logic structure and the previously obtained model in bond graph technique. The main goal of the designed controller is to position the payload in the desired location without oscillations. We have exported the bond graph model of three-dimensional crane system from *Dymola* to *Simulink* and then we designed a fuzzy controller. To verify the effectiveness of the proposed control method we performed several digital simulations. Experimental results show the good system accuracy and oscillations are significantly reduced.

This paper is organized as follows. In Section 2, the three-dimensional crane system is described and the mathematical model is fully developed. The simulation model of the described system using bond graph technique is determined and discussed in Section 3. In the next Section, the fuzzy logic is developed and simulation results are presented in Section 5. The concluding remarks are given in the last Section.

2. 3D CRANE SYSTEM DESCRIPTION

Three-dimensional laboratory model of industrial crane (see Fig. 1), made by Inteco [18], is a highly non-linear electromechanical system having a complex dynamic behaviour and creating challenging control problems. It consists of a payload hanging on a pendulum-like lift-line wound by a motor mounted on a cart. The payload is lifted and lowered in the *z* direction. Both the rail and the cart are capable of horizontal motion in the *x* direction. The cart is capable of horizontal motion along the rail in the *y* direction. Therefore the payload attached to the end of the lift-line can move freely in three dimensions. The 3D crane is driven by three DC motors.

Fig. 1 The 3D crane system manufactured by Inteco

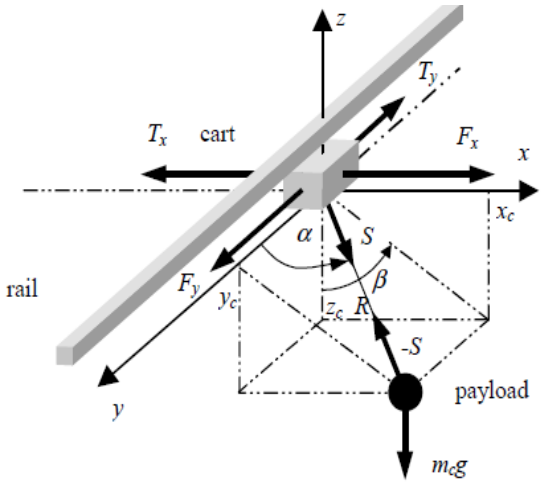

Fig. 2 Free body diagram of the 3D crane system

There are five identical encoders measuring five state variables: x_w represents the distance of the rail with the cart from the centre of the construction frame; y_w is the distance of the cart from the centre of the rail; R denotes the length of the lift-line; α represents the angle between the y axis and the lift-line; β is the angle between the negative direction on the z axis and the projection of the lift-line onto the xz plane. The schematic representation of the 3D crane system is shown in Fig. 2.

The relationships that describe the given system are [13-15]:

$$\mu_1 = \frac{m_c}{m_w},\ \mu_2 = \frac{m_c}{m_w + m_s}, \tag{1}$$

$$u_1 = \frac{F_x}{m_w},\ u_2 = \frac{F_y}{m_w + m_s},\ u_3 = \frac{F_R}{m_c}, \tag{2}$$

$$T_1 = \frac{T_x}{m_w}, T_2 = \frac{T_y}{m_w + m_s}, T_3 = \frac{T_R}{m_c}, \tag{3}$$

$$N_1 = u_1 - T_1, N_2 = u_2 - T_2, N_3 = u_3 - T_3, \tag{4}$$

where m_c, m_w, m_s – mass of the payload, cart and moving rail, respectively, 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, F_R – force controlling the length of the lift-line and T_x, T_y, – friction forces.

The load position is described by the following equations:

$$x_c = x_w + R\cos\alpha, \tag{5}$$

$$y_c = y_w + R\sin\alpha\sin\beta, \tag{6}$$

$$z_c = -R\sin\alpha\cos\beta, \tag{7}$$

$$R^2 = (y_c - y_w)^2 + z_c^2 + (x_c - x_w)^2. \tag{8}$$

Crane dynamics is described by:

$$m_c\ddot{x}_c = -S_x,\ m_c\ddot{y}_c = -S_y,\ m_c\ddot{z}_c = -S_z - m_c g. \tag{9}$$

where S_x, S_y, S_z are components of the force, i.e.:

$$S_x = S\cos\alpha,\ S_y = S\sin\alpha\sin\beta,\ S_z = -S\sin\alpha\cos\beta. \tag{10}$$

The first two DC motors control the position of the cart and the last one controls the length of the lift-line. If the flag is set to 1 and the encoder detects range over sizing, the corresponding DC motor is switched off. If the flag is set to 0 the motion continues in spite of the range limit exceeded in the encoder register. The previously described system dynamics will be used in the next Section to obtain simulation model of 3D crane system using bond graph techniques.

3. Bond Graph Model of Three-dimensional Industrial Crane

The basics elements, used in bond graph model of 3D crane system, are: the resistor *R* (dissipative element), the capacitor *C*, the inductor *I* (energy storage element), the modulated transformer *MTF*, the gyrator *GY* (conservative element), the effort and flow sources (energy source elements). There are also junction structure elements: 0-junction and 1-junction. The 0-junction is a flow balance junction or a common junction. It has a single effort on all its bonds and the algebraic sum flows is null. The 1-junction is an effort balance junction or a common flow junction. It has a single flow on all its bonds and the algebraic sum of effort is null. The effort source *Se* in *z* axis enters effort, i.e. force of gravity *mg*, while flow sources *Sf* from DC motors in *x*, *y*, *z* axis enters flows-velocity as a starting information in the process. DC motors are included individually. Junction with the identical flow *1a* presents the port with the same velocity and the sum of forces gravity, inertial force from payload and velocity from DC motor. The first derivative of positions z_c, y_c, x_c represents the corresponding velocities $\dot{z}_c$, $\dot{y}_c$, $\dot{x}_c$ of the payload. Junction *1d* is a sum of inertia of the cart and friction forces *R: Tx*. Junction *0a* is defined as a sum of velocities in functions of variables-string radius $\dot{R}$ and angular velocity $\dot{\alpha}$, where the output force from *0a* is input in junction *1d* while output bond is inertia of payload. Junction *1f*, *1g* and *1h* defines the velocities $\dot{\alpha}$, $\dot{\beta}$ and $\dot{R}$. Junction *0a, 0b, 0c* and *1a*, *1b*, *1c* are defined with the following equations:

$$0a : \dot{x}_c = \dot{x}_w + \dot{R}\cos\alpha - R\dot{\alpha}\sin\alpha \,, \tag{11}$$

$$0b : \dot{y}_c = \dot{y}_w + \dot{R}\sin\alpha\sin\beta + R\dot{\alpha}\cos\alpha\sin\beta + R\dot{\beta}\sin\alpha\cos\beta \,, \tag{12}$$

$$0c : \dot{z}_c = -\dot{R}\sin\alpha\cos\beta - R\dot{\alpha}\cos\alpha\cos\beta + R\dot{\beta}\sin\alpha\sin\beta \,, \tag{13}$$

$$1a : m_c\ddot{x}_c = -m_c g - R\sin\alpha\cos\beta + Sf_{DCmotor} \,, \tag{14}$$

$$1d : m_w\ddot{x}_w = Sf_{DCmotor} - T_x + S\cos\alpha \,, \tag{15}$$

$$1c : (m_w + m_s)\ddot{x}_w = Sf_{DCmotor} - Ty + S\sin\alpha\sin\beta \,. \tag{16}$$

Bond graph model of the DC motor (see Fig. 3) consists of two 1- junctions, two R and two I elements. There exists a common junction there exists a common junction ili there commonly exists junction..

1s and *1t* with the identical flow contains for four bonds. A PIDs controller for the positions, voltages and limiters are connected to motors. The main problem is reflected in causality and it is avoided using acausal bond graph. To derive the total acausal bond graph,two kinds of connector classes are needed to be created: *e*-connector, *f*-connector to establish acausal bond, where: the Se-element stands for the voltage and forces source; the seven I-elements represent the moment of inertia derived from the mass and the magnetic energy and the kinetic energies of the rotor and the load from DC motor; the six R-elements enable the friction and the dissipative energy in the electrical circuit; the GY-element depicts the electro-mechanical coupling; the MTF-element is associated to the power conserving rotation into translation velocities. The total acausal bond graph of the 3D crane system is illustrated in Fig. 4. It is based on the system equations (5)-(10). The model is described by three unknown coordinates of the two angular velocities.

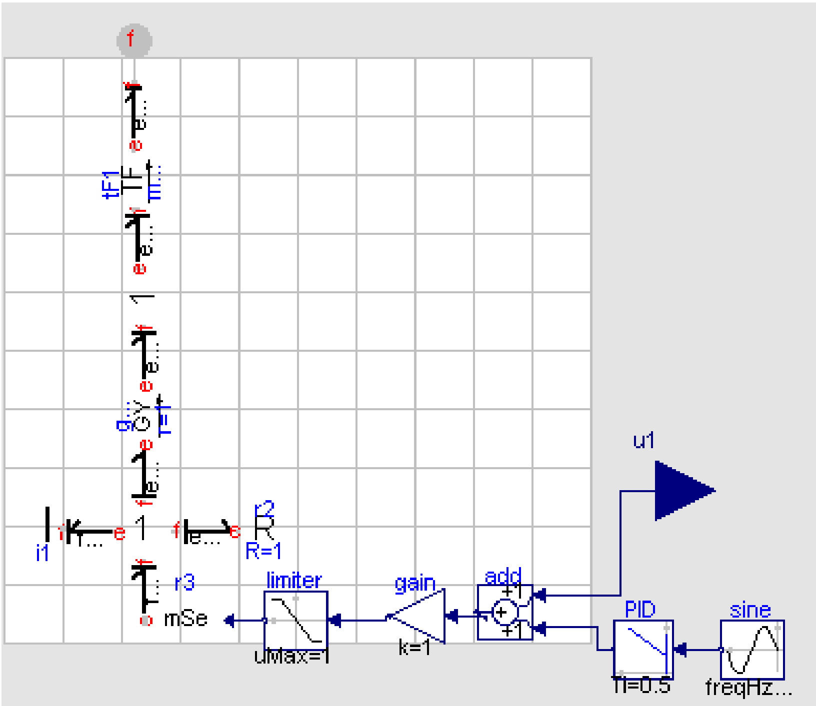

Fig. 3 Bond graph model of the DC motor in *Dymola*

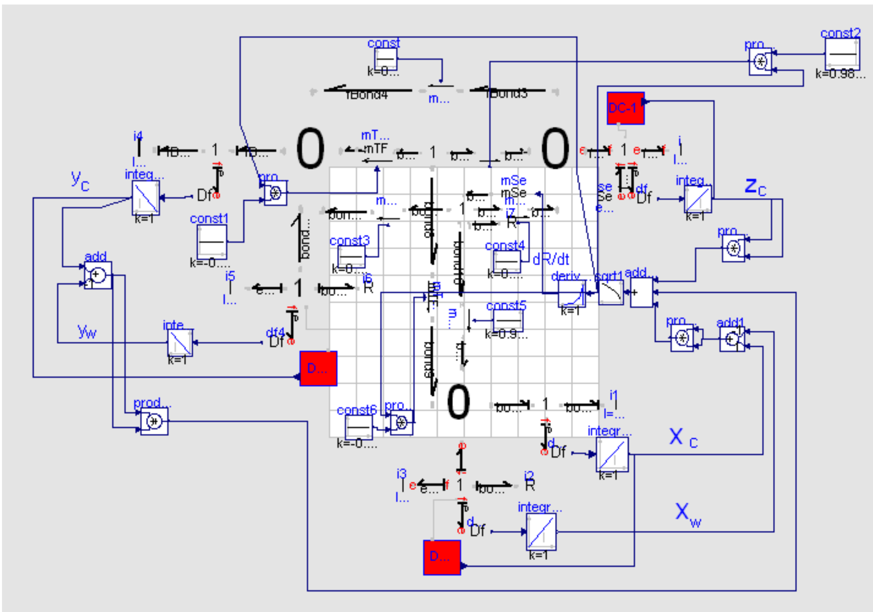

Fig. 4 Acausal bond graph model of the 3D crane system in *Dymola*

4. Fuzzy Logic Control of 3D Crane System

As we already highlighted in [13], the obtained bond graph model of three-dimensional crane system can be used as a plant for design of some control algorithms based on advance control method. The main objective in the control of 3D crane system is to position the payload in the desired location without oscillations [19]. In this paper we choose to design controller based on fuzzy logic structure. A fuzzy logic system has four blocks as shown in Fig. 6:

1. The fuzzification interface: transforms input crisp values into fuzzy values,
2. The knowledge base: contains knowledge of the application domain and the control goals,
3. The decision-making logic: performs inference for fuzzy control actions,
4. The defuzzification interface.

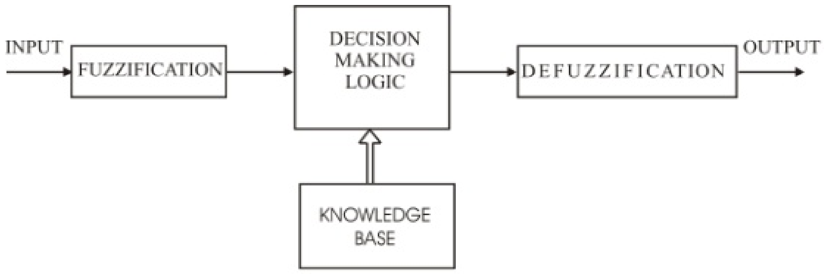

Fig. 5 Structure of fuzzy controller

Crisp input information from the device is converted into fuzzy values for each input fuzzy set using a fuzzification block. Input values of a fuzzy controller are positions of cart and payload in the direction of x, y and z axis and angle deviation α and β. The iInput set of positions deviations consists of five membership functions: negative large, target-desired position, near, medium, and large-positive distance.

The membership function for deviation in x, y and z axis are given in Fig. 6.

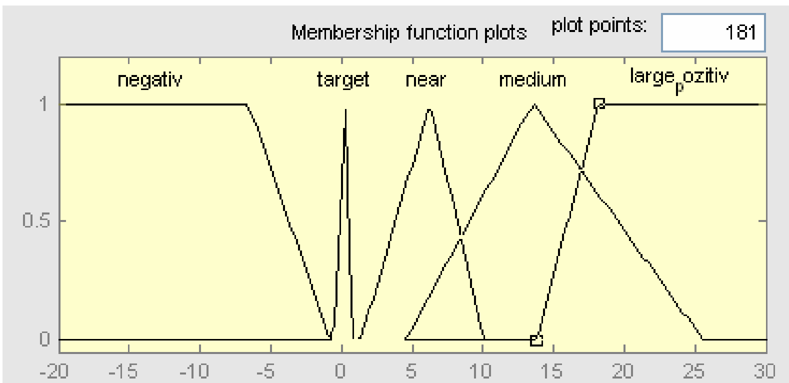

Fig. 6 Membership functions for deviation in x, y, and z-axis

The position of the payload is described by two angles α and β. Their membership functions take the shape shown in Fig. 7, with the following descriptions: negative big, negative little, target, positive medium, positive large.

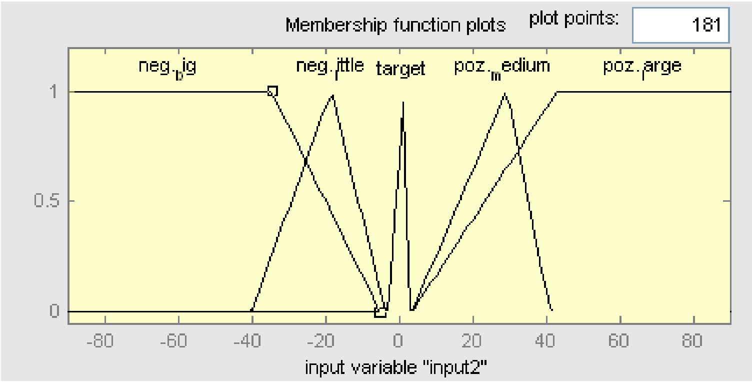

Fig. 7 Membership functions for angles α and *β*

An output value from fuzzy controller is voltage and is defined as a linguistic variable as follows: negative big, negative medium, target, positive medium and positive big.

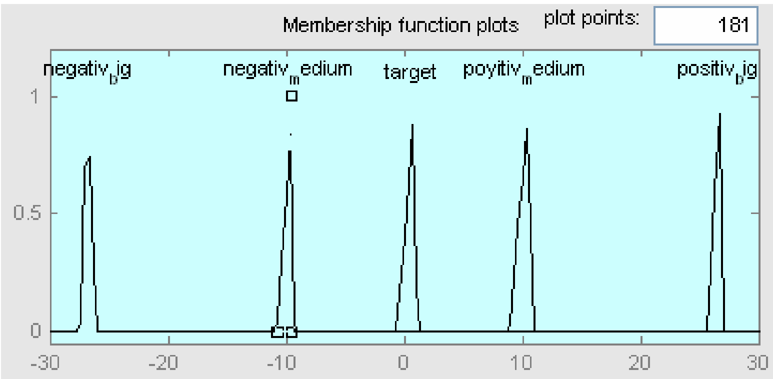

Fig. 8 Output functions from powers of DC motors

The fuzzy logic control is based on six rules, where the first input is distance, the second one is angles position and outputs are powers of the DC motors:

1. If (input1 is negative) and (input2 is target) then (output1 is positive_medium),
2. If (input1 is large_positive) and (input2 is neg._little) then (output1 is positive_big),
3. If (input1 is medium) and (input2 is neg._little) then (output1 is negative_medium),
4. If (input1 is medium) and (input2 is neg._little) then (output1 is positive_medium),
5. If (input1 is near) and (input2 is target) then (output1 is positive_medium),
6. If (input1 is target) and (input2 is target) then (output1 is target).

Such selected system parameters resulting in the control surface is given in Fig. 9.

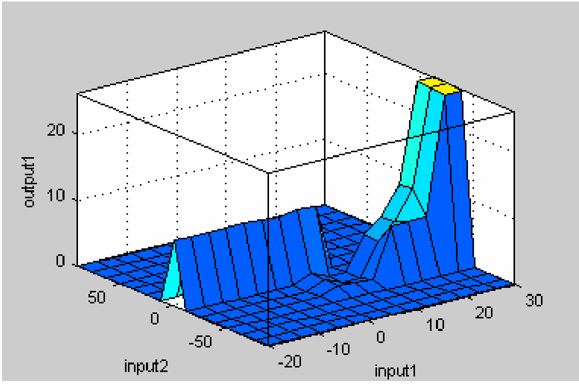

Fig. 9 Control surfaces of fuzzy controller

5. EXPERIMENTAL RESULTS

A block diagram of the exported bond graph model of 3D crane (Fig. 4) from *Dymola* to *Simulink* with fuzzy controller is shown in Fig. 10. To adjust the model for use in *Simulink* we have to define the input (power of DC motors) and output signals (x, y, z, α, β) that will be exchanged between the physical model defined in *Dymola* and the control system in *Simulink*.

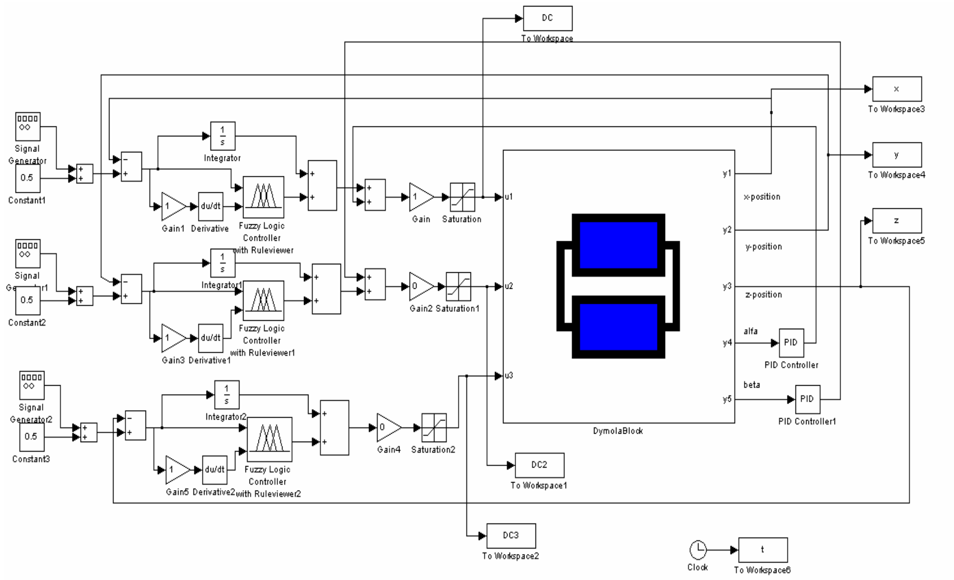

Fig. 10 *Dymola* block of 3D crane system and fuzzy logic control in *Simulink*

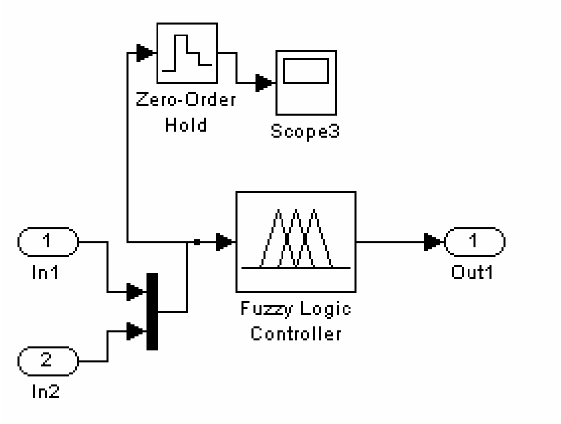

Fig. 11 Look under fuzzy mask

The validation of the model and parameters are performed by digital simulation in different conditions. The obtained results show very good control performances under a wide range of operating conditions and the undesired oscillations, during the positioning of payload cart are significantly reduced. The simulation results are presented in Figs. 12 and 13.

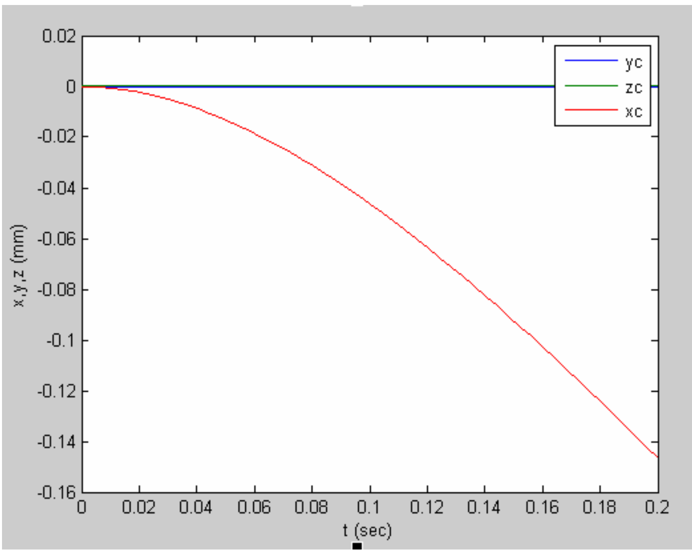

Fig. 12 Position responses for *x*, *y*, and *z*-axis

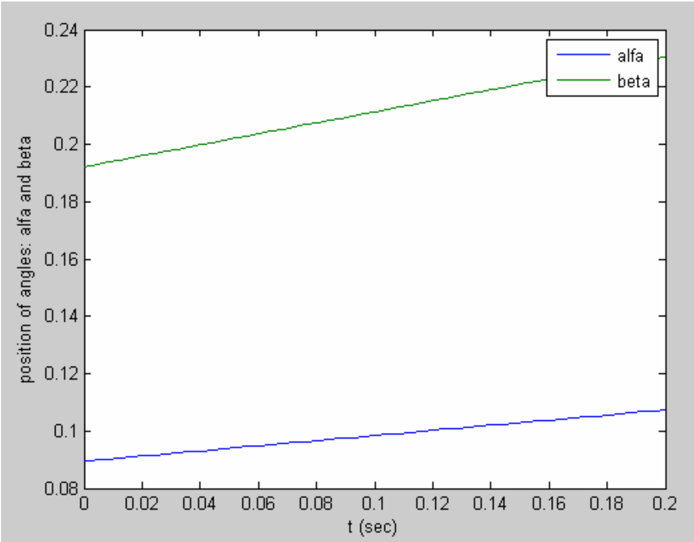

Fig. 13 Position of angles α and β

6. Conclusion

In this paper we presented the bond graph technique applied in modeling of three-dimensional (3D) laboratory crane system. First, the complete mathematical background of the considered system is given. After that, the complete process of bond graph modeling is described and the corresponding bond graph models are presented. Finally, the bond graph model of 3D crane system is tested through simulations in *Dymola* and the obtained results are compared with already existing one. It is proved that the bond graph model fully determined the 3D crane system dynamics. In addition, we propose a fuzzy controller, which gives better results compared to the already existing one. The main fuzzy controller's structure which includes connection between bond graph model in Dymola and fuzzy controllers in Simulink is presented. As it can be seen, it consists of three processes: fuzzification, fuzzy concluding, based on fuzzy rules, and deffuzification. The results show that the method described in the paper shows good system accuracy.

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