# Bond Graph Modelling and Simulation of the 3D Crane System Using Dymola

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*Abstract* – ***An application of Bond graph technique for modelling and simulation of the industrial three-dimensional (3D) crane system is presented in this paper. First, the description of considered system is given, and after that the total bond graph model is determined. In addition, several simulations, for concrete values of parameters, in Dymola are performed. Finally, the simulation results are compared with already developed one, and it is verified that obtained bond graph model determines system dynamics adequately.***

*Keywords* – **Bond graph, 3D crane, Dymola, Modelling and simulation.**

## I. 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 exchange energy using connections; these connectors represent bonds). The effort (voltage, force, pressure, etc.) and the flow (current, velocity, volume, flow rate, etc.) are generalization 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). Obtained model can be successfully tested in 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 modelling tool for various types of process [4-10]. In [11, 12] we used bond graph method for modelling of submersible pumps in water industry. The obtained model is used as an object for the control design based on orthogonal polynomials.

In this paper we present the process of modelling and simulation of three-dimensional laboratory model of industrial crane. In addition, the simulation of obtained model is performed using *Dymola* and simulation results are presented and discussed. In order to verify the effectiveness of obtained bond graph model, the simulation results are compared with already existing one and it is proved that this model fully describe the 3D industrial crane system dynamics. In future work, obtained model can be used as a plant for design of some control algorithms based on advance control method.

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## II. 3D CRANE SYSTEM DESCRIPTION

Three-dimensional laboratory model of industrial crane (see Fig. 1), made by Inteco [13], 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

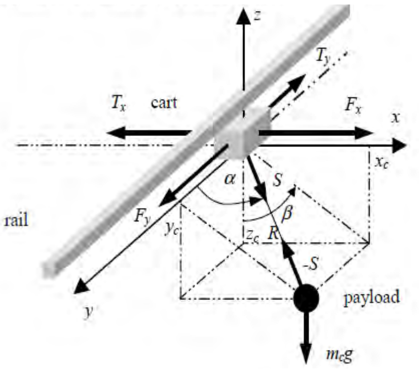


Fig. 2. Free body diagram of the 3D crane system

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; $\alpha$ represents the angle between the $y$ axis and the lift-line; $\beta$ 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 a given system are [14]:

$$\mu_1 = \frac{m_c}{m_w},\ \mu_2 = \frac{m_c}{m_w + m_s}, \quad (1)$$

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

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

$$N_1 = u_1 - T_1, N_2 = u_2 - T_2, N_3 = u_3 - T_3, \quad (4)$$

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:

$$x_c = x_w + R\cos\alpha, \quad (5)$$

$$y_c = y_w + R\sin\alpha\sin\beta, \quad (6)$$

$$z_c = -R\sin\alpha\cos\beta, \quad (7)$$

$$R^2 = \left(y_c - y_w\right)^2 + z_c^2 + \left(x_c - x_w\right)^2. \quad (8)$$

Crane dynamics is described by:

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

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

$$S_x = S\cos\alpha,\ S_y = S\sin\alpha\sin\beta,\ S_z = -S\sin\alpha\cos\beta. \quad (10)$$

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.

## III. 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 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:

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

$$\begin{aligned} 0b: \dot{y}_c &= \dot{y}_w + \dot{R}\sin\alpha\sin\beta + \\ &+ R\dot{\alpha}\cos\alpha\sin\beta + R\dot{\beta}\sin\alpha\cos\beta, \end{aligned} \quad (12)$$

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

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

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

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

Bond graph model of the DC motor (see Fig. 3) consists of two 1- junctions, two R and two I elements. There exists commonly 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, there is need to create two kinds of connector class: *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). Model is described by three unknown coordinates of the two angular velocities.

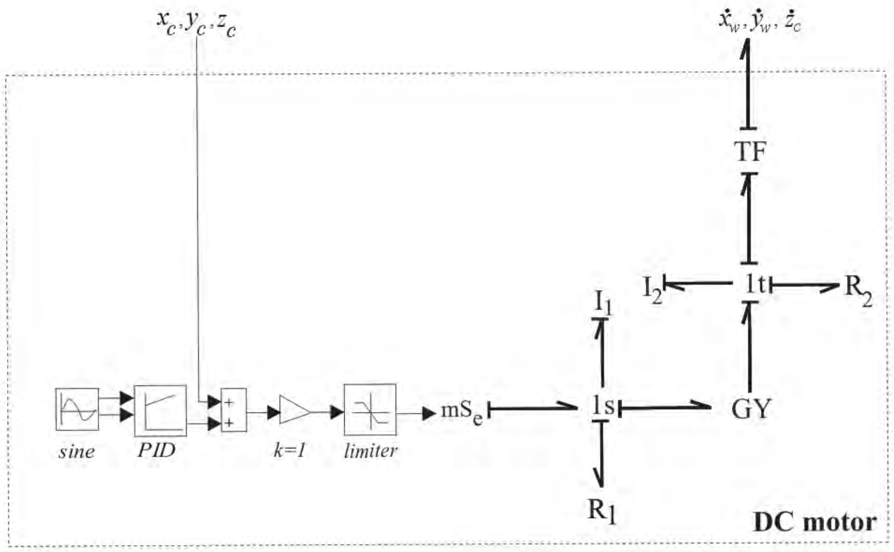


Fig. 3. Bond graph model of the DC motor

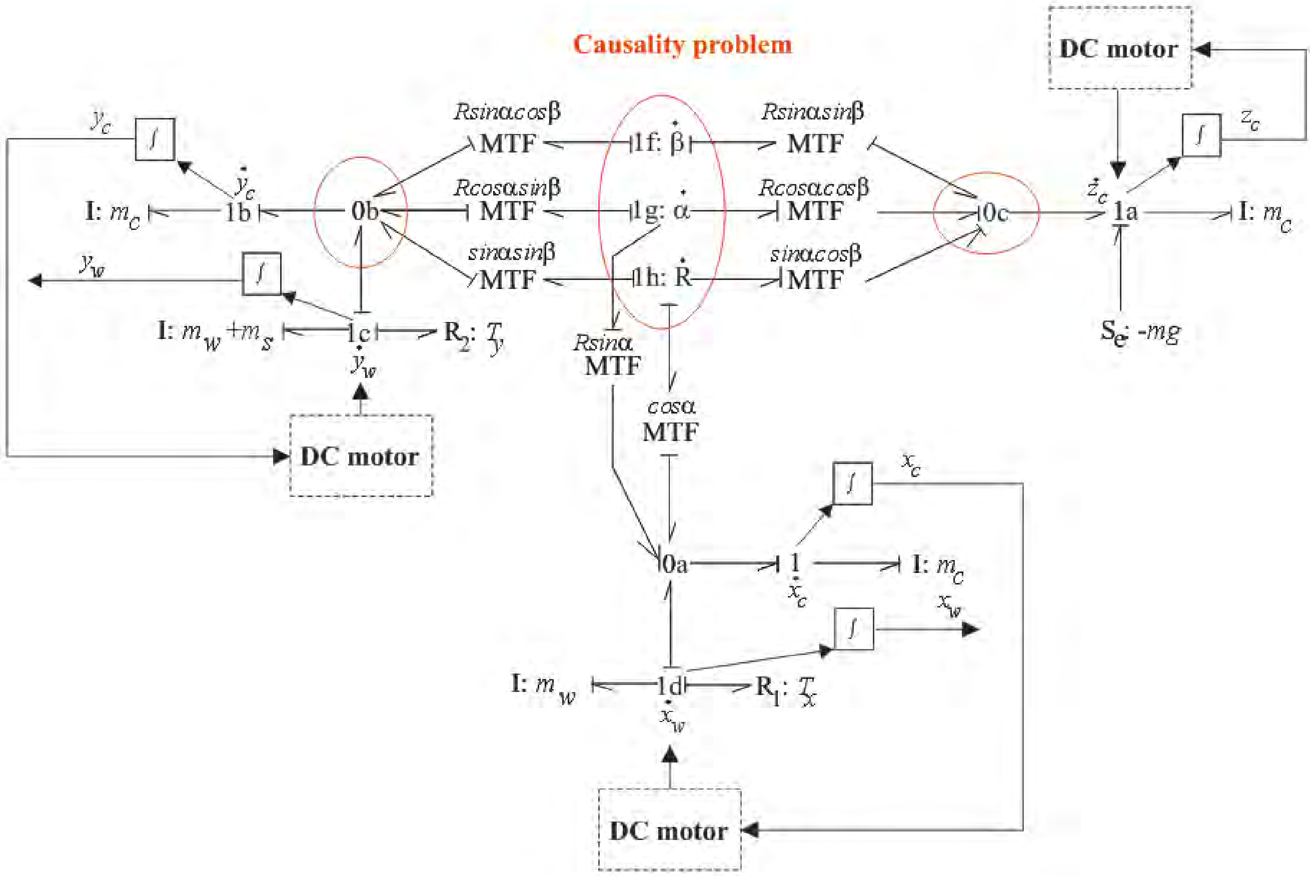


Fig. 4. Acausal bond graph model of the 3D crane system

## IV. SIMULATION RESULTS

In order to verify the efficiency of proposed method for modelling of 3D crane system and validity of obtained model, we performed the several simulations in *Dymola*. The considered parameters of simulation are: $\alpha$=10˚, $\beta$=30˚, $m_c$=0.35kg, $m_w$=0.8kg, $m_s$=0.5kg, $T_x$=0.235Nm. The parameters used for the DC motor are: $L$=0.02H; $R_1$=4Ω; $R_2$=2.5Nm/s; $J$=0.2kgm$^2$. Simulation time is $t$=0.02s.

In Fig. 5, position responses for $x$, $y$ and $z$-axis are presented. These simulation results are compared with simulation results presented in [13]. It can be noticed that obtained results (dashed lines) are very close to the existing one (solid line), which proves that bond graph model fully determines system dynamics. This is useful for student exercises where they can implement their control algorithm based on different models. Also, in some application the bond graph model is more suitable for controller design than conventional one, obtained in other graphic tool environment.

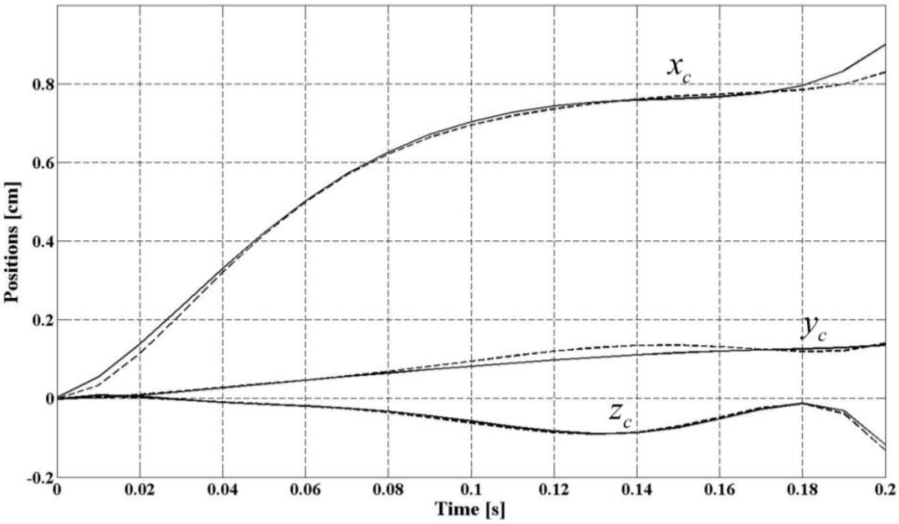


Fig. 5. Position responses for *x*, *y*, and *z*-axis

## V. Conclusion

In this paper we presented the bond graph technique applied in modelling of three-dimensional (3D) laboratory crane system. First, the complete mathematical background of considered system is given. After that, the complete process of bond graph modelling is described and corresponding bond graph models are presented. Finally, the bond graph model of 3D crane system is tested through simulations in *Dymola* and obtained results are compared with already existing one. It is proved that bond graph model fully determined the 3D crane system dynamics. In future work, this model can be used as a plant for controller design.

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