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PROCEDURE FOR VISUALIZATION AND DYNAMIC ANALYSIS OF ROBOT MANIPULATOR

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ABSTRACT
The paper proposes procedure for creating a visual model of robot manipulator. Proposed methodology assumes usage of 3D CAD models of robot links and other parts of robot manipulator. They can be prepared by suitable 3D CAD software (CATIA, SolidWorks etc.). They are exported into STL format files, and used as basic building blocks during 3D robot visual model development. To provide dynamic analysis, the dynamic model of robot manipulator is also developed in the paper. Dynamic model is created by bond graphs. Between two models – dynamic from one side and 3D geometric from the other side - a two-way inter-process communication is established to provide exchange of the necessary information. The proposed procedure is illustrated on an example of a robot manipulator with two revolute and one prismatic joint. Its dynamic model is developed by bond graphs in object oriented environment of BondSim software. Visualization is done using BondsimVisual application.
Keywords: robot manipulator, 3D CAD model, dynamic modeling, visualization

1. INTRODUCTION
In modeling and dynamic analysis of multibody systems, visualization becomes powerful tool, providing many benefits: 3D view, detection of possible collision between components of complex system, optimization of new product design, improving performances, etc. That is reason way visualization tools are included in popular software – such as Matlab/Simulink [5], Dymola [8], etc. for dynamic analysis of mechatronic systems. On the other side, technique of industrial robot programming based on creating of virtual robot environments became standard robot programming tools. Thus, the robot manufacturers develop softwares for off-line programming of the industrial robots: ABB Robot Studio, Fanuc RoboGUIDE, Kuka Sim, Kawasaki PC-Roset, etc. But, these software tools provide only the kinematic consideration.
Procedure for development of visual multibody system model is explained in the paper on the example of a robot manipulator with three joints. Also, the dynamic model of robot manipulator is developed using bond graph technique in object oriented environment of program BondSim. Visual model is defined using program BondSimVisual. Between these two models, developed from two different points of views, a two-way communication is established.
The paper is organized as follows. Kinematic and dynamic model of robot manipulator is developed in the second section. Visualization procedure is explained in the third one. The fourth section is devoted to verification of developed models.

2. BOND GRAPH MODEL OF ROBOT MANIPULATOR

Proposed visualization technique is applied on robot manipulator, shown in Fig.1a, with three degree of freedom. It is composed of three joints: first two joints are revolute and the third is a prismatic.

2.1. Kinematic model of robot manipulator

To develop kinematic model of manipulator, the coordinate frames are attached to each link: the system $O_0X_0Y_0Z_0$ is the absolute coordinate system and frames $O_iX_iY_iZ_i$ (i=1,2,3), Fig.1b, are moving jointly with the links.

Table 1. DH parameters for robot manipulator.

Link i	a_i	α_i	d_i	θ_i
1	0	$\pi/2$	L_2	$\pi/2+\theta_1$
2	L_2	$\pi/2$	0	$\pi/2+\theta_2$
3	0	0	$L_3 + d_3$	0

DH parameters that that describe position and orientation between two neighbor frames are given in Table 1. The corresponding matrices are defined by ($\sin(\theta_i)=s_i$, $\cos(\theta_i)=c_i$):

$$\mathbf{A}_0^1=\begin{bmatrix}-s_1 & 0 & c_1 & 0\\ c_1 & 0 & s_1 & 0\\ 0 & 1 & 0 & L_1\\ 0 & 0 & 0 & 1\end{bmatrix};\mathbf{A}_1^2=\begin{bmatrix}-s_2 & 0 & c_2 & -L_2s_2\\ c_2 & 0 & s_2 & L_2c_2\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\end{bmatrix};\mathbf{A}_3^2=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & L_3+d_3\\ 0 & 0 & 0 & 1\end{bmatrix}. \quad \text{... (1)}$$

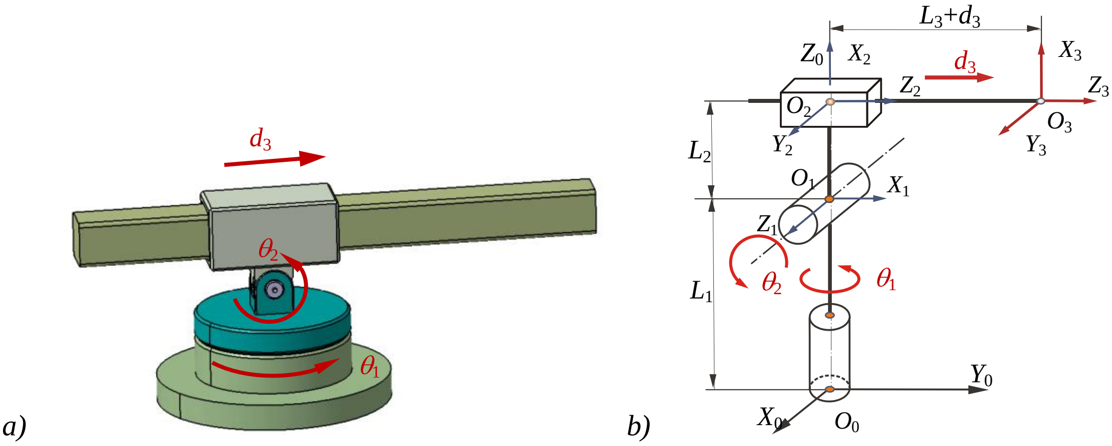


Figure 1. Robot manipulator: a) 3D model from CATIA; b) kinematic scheme.

Applying the direct kinematics leads to expressions for the position of the manipulator tip (the origin O_3 of frame $O_3X_3Y_3Z_3$) as:

$$\left.\begin{aligned} p_x &= \left[L_2\cdot\sin(\theta_2)-(L_3+d_3)\cdot\cos(\theta_2)\right]\cdot\sin(\theta_1)\\ p_y &= \left[-L_2\cdot\sin(\theta_2)+(L_3+d_3)\cdot\cos(\theta_2)\right]\cdot\cos(\theta_1)\\ p_z &= L_1+L_2\cdot\cos(\theta_2)+(L_3+d_3)\cdot\sin(\theta_2)\end{aligned}\right\}. \quad \text{... (2)}$$

2.2. Dynamic model of robot manipulator

Bond graph model of robot manipulator is developed using software package BondSim [1]. The system level of the model is depicted in Fig.2a. It is based on bond graph component models of the rigid bodies that represent the robot links and joints – the first two are rotational and the third one is prismatic. Each component is realized as a complex hierarchical model. During the building of simulation model, its mathematical model is automatically created in form of differentiation algebraic equations (DAEs), which are solved during the simulations using modified backward differentiation formulae with variable time step. Much more about bond graph modeling is given in [1].

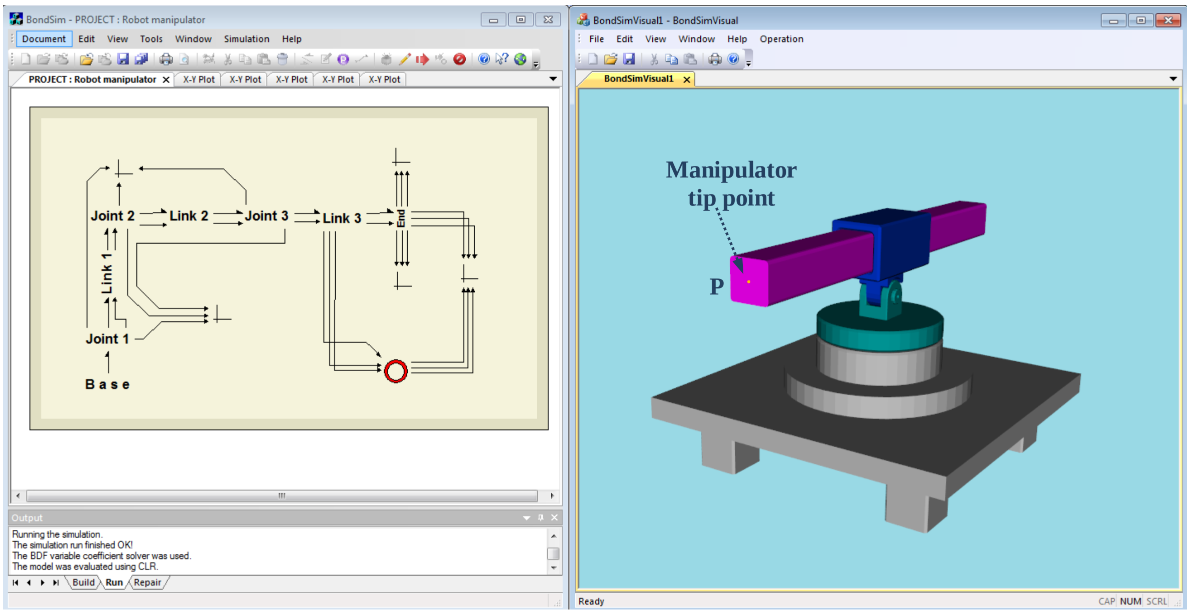
3. VISUAL MODEL OF ROBOT MANIPULATOR

To develop visual model of robot arm software package BondSimVisual is used, based on VTK (Visualization Tool Kit) C++ library. There are different ways how to create a visual 3D model. One approach is based on writing a script file in which model geometry, e.g. a robot manipulator, is defined using the primitives (cylinders, cubes, polyprisms, etc.). Another, a more comfortable approach, uses the complete assemblies for example the complete robot bases, links, joints etc., in form of STL files. These parts can be developed by a 3D CAD software, and exported into the STL files. Many 3D software packages support STL format (STL stands for 'stereolithography'). STL files can be defined in binary or ASCII formats. The binary files are smaller, but ASCII can be edited and modified following STL standards. Body surfaces in STL format are represented by mesh of triangles, which numbers and sizes directly influence the accuracy of the shape and body dimensions. VTK library that BondSimVisual uses contains STL file readers. 3D CAD model of the robot manipulator, Fig.1a, is developed using CATIA. Each of its part is saved into STL format. The script file (Table 2) defines the robot manipulator based on its parts – the base and links. The first instruction in the script defines the robot and its absolute coordinate frame $O_0X_0Y_0Z_0$ with respect to the 3D default virtual scene frame, whose origin is in the center of the scene, z-axis goes out of the screen, x-axis is to the right, and y-axis is oriented upward. The next instructions define the joints by specifying the values along the axes of the absolute coordinate frame. The limits of joint rotations are also defined.

Table 2. Part of script file for robot manipulator.

```
!-------- Robot manipulator ------------------------------------------
Robot Robot manipulator (euler -90.0 -90.0 0.0)
     Joint 1 revolute Z
     Joint 2 ( shift z 93 ) revolute X ( shift z 45 )
     joint 3 prismatic Y
     initial (0.0 0.0 0.0)
     minimum (-180.0 -40.0 -150.0)
     maximum ( 180.0  40.0  150.0)
```

Between two models – the dynamic, developed by bond graph techniques, and 3D visual one which are realized using different software packages – there is two-way inter-process communication. In this paper the dynamic model of robot manipulator sends to the visual one information on the current values of the joint variables. The visual program updates the robot position in 3D scene and returns back the coordinates of tip P (Fig.2b). Communication between two models is obtained using inter-process communication (IPC) based on named pipes [2].



a) *b)*

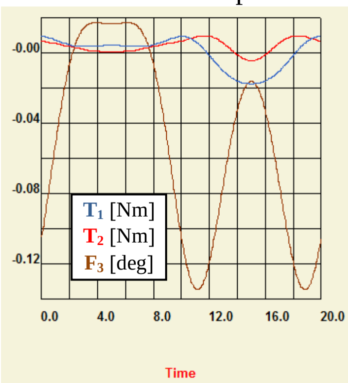
Figure 2. Robot manipulator: a) Bond graph model; b) Visual model

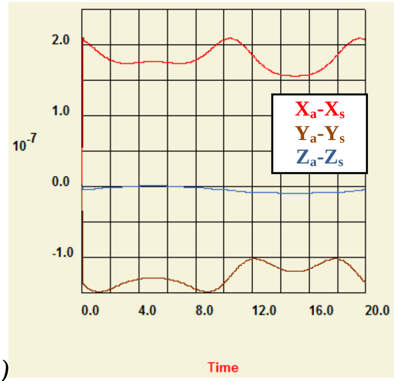
4. MODEL VERIFICATION

To verify cooperation between two developed models simple an experiment is performed. Each joint is powered by source flows that defined the joint rates and the joint variables are:

$$\begin{aligned} \theta_1 &= -160 \cdot \sin(\pi t/10), \quad [\text{deg.}] \\ \theta_2 &= -30 \cdot \sin(\pi t/10), \quad [\text{deg.}] \\ d_3 &= -150 \cdot \sin(\pi t/10), \quad [\text{mm}]. \end{aligned} \qquad \text{... (3)}$$

Mass and inertia properties of robot links are taken from CATIA 3D model. It was assumed that links are made of aluminum (mass density ρ=2710 kg/m^3). Lengths of links are L_1=0.093m, L_2=0.045m and L_3=0.2m. Simulation is performed with the time step of 0.01 s and simulation interval of 20 s. Simulation results are presented in Fig.3a-d.

a) 

b) 

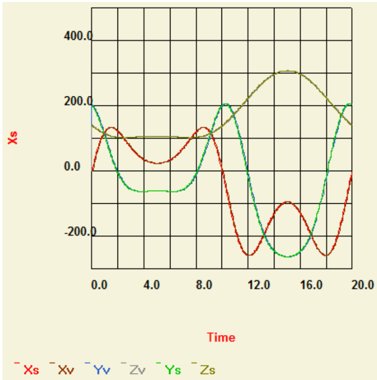
c) 

Figure 3.a) Joint torques and force; b) Difference between Tip point coordinates obtained by analytical solution (Eqs.(2)) and during simulation from bond graph model; c) Tip point coordinate obtained from bond graph dynamic model (index s) and from virtual model (index)

Joint torques and force (for the prismatic joint), obtained during simulations to develop joint variables, according to Eqs.(3) are shown in Fig.3a. Validation of developed dynamic model is done by comparison of manipulator tip coordinates obtained from bond graph dynamic model with analytical solution (according to solution of direct kinematic model, Eqs.(3)). Differences between these coordinates are depicted in Fig.3b. The obtained accuracy is good (1e-7 m). The tip robot coordinates from dynamic and virtual (visual) model are also compared, Fig.3c, showing a good agreement.

5. CONCLUSION

Taking into account the importance and benefits obtained by visualization during analysis of multibody system's behavior, the paper proposes way to develop cooperating dynamic and 3D visual models of multibody systems. The proposed procedure is explained on example of robot manipulator consisting of two revolute and one prismatic joint. The visual and dynamic model for robot manipulator is developed in the paper. Between them during the simulation there is two-way communication. The robot trajectories obtained are compared showing a good agreement.

6. REFERENCES

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