Web-based virtual reality for simulation of a heavy manipulator with a freely suspended payload

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Abstract. The paper presents the development of a Web-based Virtual Reality (VR) environment for simulation and visualization of the motion of a hydraulically driven heavy manipulator with a freely suspended payload. Two main problems are resolved in the paper. First, a combined mathematical model of the manipulator, considered as a 2 DOF discrete mechanical model is derived. It represents the dynamics of the two key functional subsystems of the manipulator – mechanical subsystem, consisting of a link and freely suspended payload and hydraulic subsystem, consisting of a hydraulic cylinder. Second, by the use of the contemporary Web technologies a VR environment for simulation, visualization and animation of the obtained results is developed. The produced VR environment is easy reused and shared with other users and thus considerably facilitates the design, investigation, and e-learning of such type of system.

1. Introduction
During the last decades, the computers became an indispensible part of the engineering design process of the mobile and stationary heavy lifting manipulators and similar hydraulically driven manipulators. To effectively deal with the growing complexity of such type of systems and to introduce the new designs to market faster, a large variety of CAE products which facilitate the design, analysis or E-learning of machines and mechanisms are used by the designers. Such type of systems include modules for preprocessing, numerical analysis and results post-processing with possibilities to resolve a large variety of tasks – from motion simulation (providing information for the position, velocity, acceleration, joint reactions, inertial forces and power requirements of all the components of a moving mechanism) \cite{1} to Finite Element Analysis (providing information about stresses, deformations and vibration modes) \cite{2}. Despite the widespread distribution of the CAE systems due to their undeniable advantages, they cannot be considered as an “ultimate and universal design tool” for the practicing engineer. One of the reasons for that is the evolving during the last years need to consider the technical systems, independently of their scale, as consisting of interacting subsystems from different physical domains and having its own dynamics. An established approach is to use dedicated software tools for modeling of the different subsystems and by co-simulation to investigate the overall system behavior \cite{3}. Another widely adopted approach for the multi-domain system model development is the use of the open source \cite{4} or commercial \cite{5, 6} software tools for modeling of integrated and complex mechatronic systems.
Software systems where active involvement of the user in the system model development is required are becoming increasingly popular [7, 8]. Web-based platforms and client-server systems [9-11], exploiting the advantages of the network computing provide valuable opportunities to use standard libraries for computation, visualization, animation and results plotting.

However, despite the vast number of approaches and available software systems supporting the design process, the model development is a time consuming and tedious process. The issue of the effective design and investigation of the heavy manipulator considered as a multi-domain physical system and results visualization and animation is still open from the point of view of the effectiveness, easy reuse and sharing with other users. The general aim of the presented paper is by using the advantages of the contemporary Web technologies to develop a prototype of a Web-based Virtual Reality (VR) environment for simulation, visualization, and animation of the motion of a hydraulically driven heavy manipulator, considered as an integrated multi-domain physical system. The produced VR environment will considerably facilitate the design, investigation, and E-learning of such type of system. A key issue in the software system development is the derivation of a mathematical model, properly representing the jointly dynamic behavior of the mechanical and hydraulic functional subsystems of the manipulator.

2. Development of a mathematical model of the system

A discrete 3D model of a heavy lifting manipulator with a freely suspended payload is shown in figure 1. It consists of a fixed base 1 and three rotating links: a column 2, rotating about the vertical axis; an arm 3 and forearm 4, both rotating about horizontal axes to determine the payload 5 motion. The manipulator hydraulic drive system consists of a rack and pinion mechanism 6, intended for column rotation, and hydraulic cylinders 7 and 8, intended for arm and forearm rotation respectively. All crane elements are considered as rigid.

For the current study, the manipulator is regarded as a planar two-link kinematic chain with two revolute joints. The column 2 and arm 3 are fixed, the forearm 4 and payload 5 are driven in the vertical plane by the hydraulic cylinder 8 through a four-bar linkage. In order to derive a dynamic model suitable for the study of the link motions, in the current paper we make the following assumptions: 1) the payload is considered as a point mass; 2) the stiffness of the links is neglected and they are considered as rigid bodies; 3) the inertia properties of the hydraulic cylinder and linkage are included into the inertial parameters of the forearm; 4) the backlashes and the friction forces in the joints are neglected.

2.1. Mathematical model of the mechanical subsystem

Figure 2 shows a layout of the manipulator with the consideration of the payload swinging. The mechanical system is modeled as an open kinematic chain undergoing planar motion. The links are
interconnected by rotational joints and are subject to forces generated by the hydraulic actuator and gravity. Each link is characterized by its geometrical and inertia parameters. Investigation of the dynamic behavior requires the solution of the forward dynamics problem for a mechanism with two rotational degrees of freedom – generalized coordinate \( \theta_1 \) describing the rotation of the forearm and \( \theta_2 \), describing the rotation of the rope together with the payload.

\[ \begin{align*}
\left( \mathbf{L}_a \right)_{ij} &= \mathbf{L}_{ij} - \mathbf{L}_{i}\mathbf{L}_{j}^T, \\
\mathbf{L}_{ij} &= \left[ \begin{array}{c}
\cos \alpha \\
\sin \alpha \\
0
\end{array} \right], \\
\mathbf{L}_{i} &= \left[ \begin{array}{c}
\cos \alpha \\
\sin \alpha \\
0
\end{array} \right], \\
\mathbf{L}_{j} &= \left[ \begin{array}{c}
\cos \alpha \\
\sin \alpha \\
0
\end{array} \right],
\end{align*} \tag{2} \]

Figure 2. Schematic of the mechanical and hydraulic subsystems of the manipulator.

The dynamic equations of motion of the manipulator are derived in a systematic way using the Lagrange formalism [12]:

\[ \frac{d}{dt} \frac{\partial L_a}{\partial \dot{q}_i} - \frac{\partial L_a}{\partial q_i} = Q_i, \quad (i = 1, 2), \tag{1} \]

where the Lagrangian \( L_a \) represents the difference between the kinetic \( K \) and potential \( P \) energies of the system studied; \( Q_i \) are the generalized forces associated with the generalized coordinates.

The kinetic and potential energies of the system are positive definite quadratic forms of the respectively generalized velocities \( \mathbf{q}^T = \left[ \dot{\theta}_1, \dot{\theta}_2 \right] \) and generalized coordinates \( \mathbf{q} = \left[ \theta_1, \theta_2 \right]^T \).

2.1.1. Kinetic energy of the mechanical system. As is shown in figure 2, a local coordinate system (c.s.) \( \{x_iy_i\} \) is connected to every link of the kinematic chain. The global c.s. \( \{x_0y_0\} \) is connected to the center of the forearm rotational joint \( O_1 \), the origin of c.s. \( \{x_1y_1\} \) coincides with the origin of the global c.s and \( \{x_2y_2\} \) is situated at the center of the rotational joint \( O_2 \). The transition between the local coordinate systems is performed by the use of transformation matrices in the following form:

\[ \mathbf{T}_i^j \left( \alpha, a_i, a_j \right) = \begin{bmatrix}
\cos \alpha & -\sin \alpha & a_x \\
\sin \alpha & \cos \alpha & a_y \\
0 & 0 & 1
\end{bmatrix}, \tag{2} \]

where \( i \) and \( j \) denote the numbers of the adjacent coordinate systems; \( \alpha \) is the angle between the coordinate systems; \( [a, a_i]^T \) represents the vector from the origin of c.s. \( i \) to the origin of c.s. \( j \) expressed in the c.s. \( i \). The kinetic energy of the system depends on the system geometrical configuration and the velocities of the links. Taking into account the used in figure 2 notations, the transformation matrices are: \( \mathbf{T}_1^0 \left( \theta_1, 0, 0 \right) \) and \( \mathbf{T}_2^1 \left( \theta_2, d_1, 0 \right) \).
The total kinetic energy of the system comprises the kinetic energies of the forearm $K_1$ and swinging payload $K_2$. Using the notations in figure 2 and according to König’s theorem, the total kinetic energy of the mechanical system is obtained as follows:

$$K = \sum_{i=1}^{2} K_i,$$  

(3)

where: $2K_1 = J\dot{\theta}_1^2 + m_1\left(\dot{x}_c^2 + \dot{y}_c^2\right), 2K_2 = m_2\left(\dot{x}_{O_2}^2 + \dot{y}_{O_2}^2\right)$.

In (3) the following notations are used: $\dot{x}_c$ and $\dot{y}_c$ denote the absolute velocities of the mass centers of the forearm. Similarly, $\dot{x}_{O_2}$ and $\dot{y}_{O_2}$ denote the absolute velocities of the payload. All velocities are obtained by a time differentiation of the corresponding position vectors according to the global coordinate system (c.s.). Position vectors are obtained by the use of the already defined transformation matrices:

$$^0\mathbf{r}_c = T_{c1}^0\mathbf{r}_c,$$

$$^0\mathbf{r}_{O_2} = T_{c1}^0T_{O_2}^1\mathbf{r}_{O_2},$$  

(4)

(5)

where by $^0\mathbf{r}_c = [x_c \ y_c \ 1]^T$ and $^0\mathbf{r}_{O_2} = [x_{O_2} \ y_{O_2} \ 1]^T$ are denoted the vectors of the points $C$ and $O_2$ correspondingly in the global coordinate system; by $^1\mathbf{r}_c = [L_c^0 \ L_c^0 \ 1]^T$ and $^2\mathbf{r}_{O_2} = [d_2 \ 0 \ 1]^T$ are denoted the coordinates of the same points in the corresponding local coordinate system.

Using Eqs. (3÷5), the kinetic energy of the system takes the following form:

$$2K = J + m_1\left(\dot{L}_c^0\dot{L}_c^0 + \dot{L}_c^0\dot{L}_c^0\right) + m_2\left(d_1^2 + d_2^2\right) + 2m_1d_1d_2\cos\theta_1\dot{\theta}_1^2 + 2d_2m_2\left(d_1 \cos\theta_2\right)\dot{\theta}_2\dot{\theta}_2 + m_1d_2^2\dot{\theta}_2^2$$

(6)

2.1.2. Potential energy of the mechanical system. The potential energy of the system is computed as a sum of the potential energies of the forearm $P_1$ and the payload $P_2$:

$$P = \sum_{i=1}^{2} P_i.$$  

(7)

The potential energies of the forearm and payload are computed as the work, required to raise its gravity center according to the x0-axis, i.e. they are a function of the system geometrical configuration:

$$P = g\left(m_1L_c^0\cos\theta_1 + \left(m_1L_c^0 + d_1m_2\right)\sin\theta_1 + d_2m_2\sin\left(\theta_1 + \theta_2\right)\right).$$ 

(8)

2.1.3. Differential equations of the mechanical system. Using the derived equations for the kinetic and potential energies and performing the mathematical operations in Eq. (1), the nonlinear dynamic equations of the motion are obtained in the form:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{H}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) = \mathbf{Q}.$$  

(9)

The notations used are as follows: Symmetric and positive definite inertia matrix $\mathbf{M}(\mathbf{q})_{2\times2}$, consisting of inertia terms; Vector $\mathbf{H}(\mathbf{q},\dot{\mathbf{q}})_{2\times1}$, consisting of centrifugal and Coriolis terms; Vector $\mathbf{G}(\mathbf{q})_{2\times1}$, consisting of terms, proportional to the weight of the links; Vector $\mathbf{Q}_{2\times1}$, consisting of
generalized forces and moments, associated with the respective generalized coordinates: \( \tau_i = Q_i, Q_2 = 0 \) where \( \tau \) denotes the driving torque applied to the first joint. The elements of the matrices are as follows:

\[
\begin{align*}
M_{11} &= J + m_i \left( \left( L_1 \right)^2 + \left( L_2 \right)^2 \right) + m_2 \left( d_1^2 + d_2^2 \right) + 2m_2d_1d_2 \cos \theta_2, \\
M_{21} &= M_{22} = d_2^2 \cos \theta_2; \\
M_{22} &= m_2d_2^2; \\
H_{11} &= -d_1d_2m_2 \sin \theta_2 \left( 2\dot{\theta}_2 + \dot{\theta}_2^2 \right), \\
H_{21} &= d_1d_2m_2 \sin \theta_2\dot{\theta}_2^2; \\
G_{11} &= g \left( L_1 + d_1m_2 \right) \cos \theta_1 + m_2d_2 \cos \left( \theta_1 + \theta_2 \right) - m_1L_c \sin \theta_1, \\
G_{21} &= m_2gd_2 \cos \left( \theta_1 + \theta_2 \right).
\end{align*}
\]

2.1.4. Determination of the driving torque. The mapping \( \tau(F) \) of the hydraulic cylinder force \( F \) to the joint torque \( \tau \) is established utilizing the principle of virtual work [12]. It allows the formulation of the required equations without having to consider the forces generated in the linkage joints. The layout of the linkage is shown in figure 3 and using the adopted notations one can write:

\[
\tau = -F \frac{L_1 \sin \left( \varphi_1 - \varphi_2 \right) \sin \left( \varphi_1 - \varphi_2 \right)}{\sin \varphi_1 - \varphi_2},
\]

where all angles are measured from the arm axis \( n-n \).

**Figure 3.** Layout of the forearm driving mechanism.

Using the notations in figure 3 and performing position analysis of the considered linkage one can compute the needed angles by the sequential application of the following equations:

\[
\begin{align*}
A &= -2L_2 \left( b \cos \gamma + L_3 \cos \theta_1 \right); \\
B &= -2L_2 \left( b \sin \gamma + L_3 \sin \theta_1 \right); \\
D &= \sqrt{A^2 + B^2}; \\
\sigma &= \text{atan2} \left( B/D, A/D \right); \\
C &= b^2 + L_3^2 + L_4^2 - L_5^2 + 2bL_3 \cos (\gamma - \theta_1); \\
\varphi_2 &= \sigma + \arccos \left( -C/D \right); \\
\cos \varphi_1 &= \left( a \cos \alpha + L_2 \cos \varphi_2 \right) / L_4; \\
\sin \varphi_1 &= \left( a \sin \alpha + L_2 \sin \varphi_2 \right) / L_4; \\
\varphi_1 &= \text{atan2} \left( \sin \varphi_1, \cos \varphi_1 \right).
\end{align*}
\]
\[
\cos \varphi_4 = \left( b \cos \gamma + L_s \cos \theta_i - L_s \cos \varphi_2 \right) / L_4; \tag{20}
\]
\[
\sin \varphi_4 = \left( b \sin \gamma + L_s \sin \theta_i - L_s \sin \varphi_2 \right) / L_4; \tag{21}
\]
\[
\varphi_4 = \arctan\left( \sin \varphi_4, \cos \varphi_4 \right). \tag{22}
\]

The velocity of the piston can be determined by the following equation:
\[
\dot{x} = \dot{L}_i = -\dot{\theta}_i \frac{L_s \sin (\varphi_1 - \varphi_2) \sin (\varphi_4 - \varphi_1)}{\sin (\varphi_4 - \varphi_1)}. \tag{23}
\]

2.2. Mathematical model of the hydraulic subsystem

In figure 2 is shown a fragment of the manipulator hydraulic subsystem. The flow to the cylinder is controlled by the spool direction control valve. Two double cross-over relief valves PRV1 and PRV2 are incorporated in the hydraulic circuit in order to relieve the excessive pressure caused by the sudden closure of the direction control valve or occurred inertial loads during the motion of the links. The force in the hydraulic cylinder is calculated as a function of the chambers pressures \( p_1 \) and \( p_2 \):
\[
F = p_1 S_1 - p_2 S_2 - b \dot{x}, \tag{24}
\]
where by \( b \) is denoted the viscous friction coefficient; by \( \dot{x} \) is denoted the velocity of the piston; by \( S_1 \) and \( S_2 \) are denoted the piston and piston minus rod areas correspondingly.

A simplified dynamical model of the hydraulic system is presented under the following assumptions: constant supply pressure, compressible oil, and absence of oil leakage in the hydraulic system. Based on the continuity equation [13] for the compressible oil and referring to figure 2, one can write the equations for the pressures in the hydraulic cylinder chambers:
\[
\dot{p}_1 = \left( \frac{\beta}{V_1 + S_1 x} \right) \left( Q_1 \dot{x} - Q_1^i \right); \tag{25}
\]
\[
\dot{p}_2 = \left( \frac{\beta}{V_2 + S_1 (h - x)} \right) \left( S_1 \dot{x} - Q_2 - Q_2^i \right), \tag{26}
\]
where \( h \) is the hydraulic cylinder stroke, \( \beta \) is the fluid bulk modulus, \( V_1 \) and \( V_2 \) are the constant oil volumes, subjected to compression. The flow rates \( Q_1 \) and \( Q_2 \) through the direction control valve are determined by the following equations:
\[
Q_1 = \begin{cases} 
\text{if } x_s \geq 0 \text{ then } & c_d w x_s(t) \sqrt{\frac{2 |p_s - p|}{\rho}} \text{sign}(p_s - p) \\
\text{else } & c_d w x_s(t) \sqrt{\frac{2 |p_s - p_0|}{\rho}} \text{sign}(p_s - p_0)
\end{cases} \tag{27}
\]
\[
Q_2 = \begin{cases} 
\text{if } x_s \geq 0 \text{ then } & c_d w x_s(t) \sqrt{\frac{2 |p_s - p_0|}{\rho}} \text{sign}(p_s - p_0) \\
\text{else } & c_d w x_s(t) \sqrt{\frac{2 |p_s - p_2|}{\rho}} \text{sign}(p_s - p_2)
\end{cases} \tag{28}
\]
where \( c_d \) is the orifice discharge coefficient, \( w \) is the direction control valve area gradient, \( x_s(t) \) is the direction control valve opening, represented as a function of time, \( \rho \) is the oil density, \( p_s \) is the supply pressure, \( p_0 \) is the drain pressure.
If the dynamics of the relief valves is neglected and turbulent flow is assumed, then the flows \( Q'_i \) \((i=1,2)\) through the valves PRV1 and PRV2 correspondingly is governed by the equations:

\[
Q'_i = c_d A_i \left( \Delta p'_i \right) \sqrt{\frac{2}{\rho} \left| \Delta p'_i \right| \text{sign} \left( \Delta p'_i \right)}, \quad i = 1, 2,
\]

where the pressure-dependent orifice passage area \( A_i(\Delta p_i) \) is described by the following piecewise linear function:

\[
A_i(\Delta p_i) = \begin{cases} 
0 & \text{if } \Delta p'_i \leq p_{\text{set}} \\
\frac{A_{\text{max}}}{p_{\text{reg}}} (\Delta p'_i - p_{\text{set}}) & \text{if } p_{\text{set}} < \Delta p'_i < p_{\max} \\
A_{\text{max}} & \text{if } \Delta p'_i \geq p_{\max}
\end{cases}
\]

where \( \Delta p_i \) is the relief valve pressure differential for valve \( i \), \( A_{\text{max}} \) is the fully open relief valve passage area, \( p_{\text{set}} \) is the relief valve preset pressure, \( p_{\text{reg}} \) is the relief valve regulation range, \( p_{\max} \) is the valve pressure at the maximum opening, and \( c_d \) is the orifice discharge coefficient.

3. Experimental setup and validation of the mathematical model

The experimental setup with a kinematic structure, similar to the considered manipulator (figure 1) is used to obtain experimental data for the force in the forearm hydraulic cylinder (figure 1, pos.8). The experimental setup consists of (figure 4): a rotating column 1, an arm 2, a forearm 3 and a hydraulic power unit 4. The mechanical structure is equipped with sensors for measuring the pressures at the cap end and the rod end of the forearm 6 and arm 5 driving cylinders; 2) the displacement of the arm and the forearm driving cylinders 7 and 8. Analog outputs from the sensors are transmitted to the computer measurement system 9 by the use of an analog-to-digital converter. For the simulation of the manipulator working cycle has used the law of motion of the spool of the hydraulic directional control valve, shown in figure 5. This pattern corresponds to the following sequence of the forearm motion – forearm raising (from initial angle \( \theta_1 = -15^\circ \) to angle \( 24.5^\circ \)), dwell in the upper position and lowering to the initial position.

![Figure 4. View of the small scale manipulator and sensor placement.](image-url)
Figure 5. Law of motion of the valve spool.

The following numerical values of the system parameters are used: \((x_v)_{\text{max}} = 0.0005 \text{ m}, t_0 = 0 \text{ s}, t_1 = 0.05 \text{ s}, t_2 = 10.15 \text{ s}, t_3 = 10.2 \text{ s}, t_4 = 14.4 \text{ s}, t_5 = 19.5 \text{ s}, t_6 = 19.55 \text{ s}, t_7 = 14.4 \text{ s}, t_{e} = 24 \text{ s}, L_2 = 0.292 \text{ m}, L_3 = 0.292 \text{ m}, L_4 = 0.2 \text{ m}, L_5 = 0.147 \text{ m}, a = 0.908 \text{ m}, b = 0.122 \text{ m}, \alpha = 100, \gamma = 320.13^\circ, S_1 = 1.96\times10^{-3} \text{ m}^2, S_2 = S_1/2.08, V_1 = V_2 = 35.7\times10^{-5} \text{ m}^3, h = 0.5 \text{ m}, w = 0.003, c_d = 0.62, \beta = 1\times10^9 \text{ Pa}, p_l = 20 \text{ MPa}, p_0 = 0, \rho = 855 \text{ kg/m}^3, b = 85000 \text{ Ns/m}, d_1 = 2 \text{ m}, d_2 = 1.1 \text{ m}, J = 80 \text{ kg.m}^2, m_1 = 100 \text{ kg}, m_2 = 400 \text{ kg}, g = 9.81 \text{ m/s}^2, L_1^e = 1 \text{ m}, L_2^e = 0.1 \text{ m}.

The experimental data for the driving hydraulic cylinder (figure 4, pos.8) force, computed by the use of the measured chamber pressures, is shown simultaneously with the obtained by the presented mathematical model hydraulic cylinder force. Although some differences are observed during the duty cycle, the good correlation between the experimental data and simulation results allows us to conclude that the adopted mathematical model may confidently be used to simulate the dynamic problems present. The differences between the curves are mainly due to the simplified mathematical model and inaccuracies in determining the numerical values of the system parameters.

Figure 6. Experimentally and theoretically obtained graphs of the forearm hydraulic cylinder force, pos.1 – experimental data; pos.2 – theoretical data.

4. Development and testing of a Web-based Virtual Reality environment

The system of equations (9-30) describing the system dynamical behavior is programmed in Matlab environment and an available routine for the solution of stiff differential equations is used. In addition, functionality for performing input-output operations is added. The Matlab file is compiled and is used for the development of a Web-based software system for simulation of the manipulator motion. The block scheme of the software system, represented in figure 7 is described briefly as follow:
Figure 7. Framework of the developed experimental Web-based system.

1) The users request a Web page/resource by entering the Web page address or clicking on a link to it;
2) The server [14] sends back the requested HTML page with an initial information “FORM” tag on it (the URL of the CGI application is specified as a part of the “FORM” by using the attribute “ACTION”);
3) The form’s fields are filled out and the data are sent to the Server;
4) The Common Gateway Interface (CGI) is a part of the Web’s Hypertext Transfer Protocol (HTTP) and by using CGI Web server passes user’s request to the Matlab executable file.
5) The server receives data back from the “exe” file as a HTML5 [15] page containing links to:
   - X3DOM (JavaScript framework for the creation of declarative 3D scenes in Web pages, without need to use any plugin for to display X3D scenes by using WebGL enabled browsers);
   - X3D (eXtensible 3D graphics) [16] model of the manipulator;
   - JavaScript file (JS) - assures main functionality in the system: a) adds parts to the X3D model according to the request of the user and finishes building of the model of manipulator; b) controls the simulation process by getting calculation data from the Matlab CGI executable application and by the use of JavaScript methods “getElementById” (access the objects in the scene marked by the values of the attributes “id”) and “setAttribute” (change the values of the attributes “translation” and “rotation”) the movements of the objects are realized; c) by capturing keyboard events additional functionality is added - for the payload trajectory plotting and for changing some parameters of the scene visualization;
6) Generated, as it is described above, HTML5 Web page is forwarded back to the user.

The manipulator is depicted in figure 8 (a) and its 13 modeled elements are marked by numbers. By using points (marked by “P” and number) are shown the connection places between elements (including the axes of relative rotation). The model of the manipulator is developed by the use of the X3D language – XML (eXtensible Markup Language) based language for 3D modeling. By the XML language models are presented in a tree structure (hierarchical) in compliance with the syntax, defined in the World Wide Web Consortium standard.

Because the model of the manipulator is not a pure tree structure and there are three cycles shown by dashed lines (see figure 8), the X3D model option for the inheritance [17] of the movements is used. The dashed connections are removed in order to transform the structure of the model into a tree (corresponding to the X3D language) and in addition to calculate at every simulation step the geometrical configuration of the triangles \( P_3P_4P_5 \), \( P_5P_6P_7 \) and \( P_6P_7P_8 \) (figure 8) according to the specific geometric constraints.

In figure 9 are shown work screens of the developed 3D simulation scene and payload trajectories for different initial values of the generalized coordinates. As additional information, different output characteristics of the model can be plotted - for example, in figure 10 (a) and (b) are shown, correspondingly, the simulated curves of the hydraulic cylinder force and the hydraulic cylinder pressures.
Figure 8. Structure of the model of manipulator.

Figure 9. 3D simulation scene and the payload trajectory for different user’s inputs.

Figure 10. Output characteristics: (a) Time evolution of the hydraulic cylinder force; (b) Time evolution of the pressures in the hydraulic cylinder chambers: 1 – piston end chamber; 2 - rod end chamber.

5. Conclusions

This paper introduces the development of an integrated Web-based Virtual Reality environment for simulation and visualization of the motion of a hydraulically driven heavy manipulator with a freely suspended payload. The iterative nature of the design process requires multiple repetitions of the same actions leading to the design of a competitive manipulator, satisfying predefined requirements. The developed Web-based software system can significantly shorten the design time and reduce the cost of
the design work. The animation capability allows the user to thoroughly understand the machine behavior during performing various motions. Presentations of the experiments are done through realistic Web visualization, capable to show to the learner processes or relationships which are not usually visible. The high-quality 3D models contribute to the intuitive perception of information and therefore provide significant educational potential. As a result of the practical tests performed, it can be concluded that the developed system is of great value and it can serve as a basis for the development of a system with greater design capabilities. As a future work we can point out the development of a fully-featured software system with the addition of a database of 3D models of machines and computational modules.

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