Digital twin for faster than real-time simulation of mobile crane operations

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Abstract. The article discusses the problem of real-time prediction of the mobile crane movement based on the analysis of the dynamic and kinematic models of the crane. These models form the digital twin that can be used to facilitate the crane operation. As the crane displacements can be comparable to the load dimensions and the crane can move rather fast, thus the crane dynamics, rather than kinematics, becomes more important in its movement prediction. However, in order to be calculated faster than real-time the model should be simplified. The article considers an example of the mobile crane for which two models are developed: the detailed reference model and the simplified model, which includes the dynamic and kinematic equations. The accuracy and the calculation speed of the simplified model are estimated with respect to the reference model. Two models are compared and some assumptions are proposed for building the models for the faster than real-time calculations required for the movement prediction of mobile cranes.

Keywords: digital twin, simulation, modeling, real-time.

1. Introduction

The Digital Twin concept provides the tool for improving the features of various systems by analysing the output of the system's model – digital twin. The use of simulation models is not a new idea but the capability of feeding them with the real time data concurrently with the actual system has recently become a very popular approach. This capability arises on the basis of the advantages of networking and computing speed. The wide and natural adoption of the concept is through the Internet of Things (IoT). Many applications of the digital twin are developed [1]. They can be divided into the two large areas: analysis of very complex systems (like plants or transportation systems) and real-time analysis of relatively small systems (like a vehicle or a human body). The first area deals with a huge number of processes that take place in a large and complicated model. This approach is very close to the well known simulation modelling. The second approach uses simpler models but often requires real-time interactions. It is sensitive to the networking speed and computational speed [2].

In this paper, we discuss the use of digital twin for the faster than real time behaviour of the model that provides the capability of making real-time decisions on the basis of the modelling. We consider the problem of controlling mobile machines. The digital twin uses the model of the machine and its environment to facilitate the control task. For example, the use of the crane or excavator in a limited environment carries a risk of collisions. The digital twin can help the operator to avoid them by fast trajectory computation based on the control input made by the operator. The less experienced is the operator and the more responsible is the work or environment the more useful is the help. As an example of responsible application the ship operating in the narrow bay can be considered.

To perform faster than real-time the model should be very fast especially for applications in which the machine's response time is small. For that reason the model should be simplified to reduce the simulation time as much as possible. The problem arises of making such model simplification that shortens the calculations but retains the accuracy of the parameters valuable for the task of control.

As an example we consider the task of operating the mobile crane in the limited environment. In such a case an inexperienced operator can easily damage the nearby objects or the payload by misoperating the crane. Much research has been done about the operation of cranes. When dealing with collision prevention the kinematics of the crane are usually considered [3]. The reason is that collision prevention is especially important on large construction sites where the loads of high dimensions and weight are operated and where many people and technical devices work. The cranes being used in such cases have large inertia and large response times and move the loads to long distances. That is why the kinematics of the crane substantiallydetermine their trajectories and dynamics are of small importance. In contrast when small mobile cranes are considered the distances are short and are comparable with the size of the load. In such situation the dynamics of the crane play more significant role as the response time is small and the movement can be fast. It is easier for the operator to make a mistake with short distances and fast movement. The consequences of collisions in small cranes operations are not so important but we consider this problem because it gives the working example for investigation of faster than real-time calculations. The results could be used in more important applications like cars collision prevention or remote control of robot actuators.

As an example in this work, the mobile crane PATU-655 is chosen. This crane is hydraulic actuated, has variable boom length and has the maximum load of 500 kg at the maximum boom length. The crane has five hydraulic cylinders. The first two are included in slew mechanism, which provides thecrane rotation around the vertical axis. The next two cylinders act through the joints raising the booms and the fifth one is mounted inside the boom and controls the extension of the boom.

In this work, the two dynamic models of the example crane are developed. The first one is created using commercially available software such as MATLAB/Simulink. This model includes detailed structure of the crane as well as the models of hydraulic cylinders. We use this model as a reference to estimate the accuracy of the second model that is intended for faster than real-time calculations. That second model is built from scratch using dynamic equations and is aimed to be calculated by a computer program specifically created for this task.

2. Reference model

For the research purposes a detailed reference model of mobile crane is developed (see figure 1). The model captures the dynamics of the crane and is created in MATLAB/Simulink using the features provided by Simscape Multibody and Simscape Fluids. The model is built using the results obtained in [4].

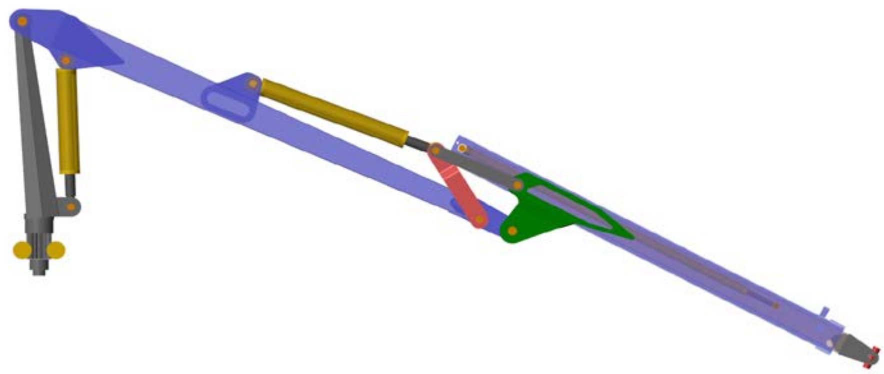

Figure 1. View of the reference model in Simscape Multibody Mechanics Explorer.

For the modelling purposes,a number of assumptions are made. The constituting parts of the crane are modelled as rigid bodies and the friction forces in the joints are neglected.

The model consists of the following parts: slew mechanism, pillar, main lifting boom, system of four interconnected side links, outer boom, and extension boom. The inertia properties of the bodies are calculated from their geometry using 3D CAD drawings of the example crane. All the parts are interconnected either with revolute or prismatic joints as shown in figure 2. At the end of the extension boom the load mass is located. The actuation of the model is provided through the models of double-acting asymmetrical hydraulic cylinders. The dimensions of the hydraulic cylinders correspond to those that are used in the real mobile crane. As the input, the pressure values for the plus and minus chambers of these cylinders are supplied. The output of the model is presented as coordinates of the carne tip position with respect to the world coordinate system.

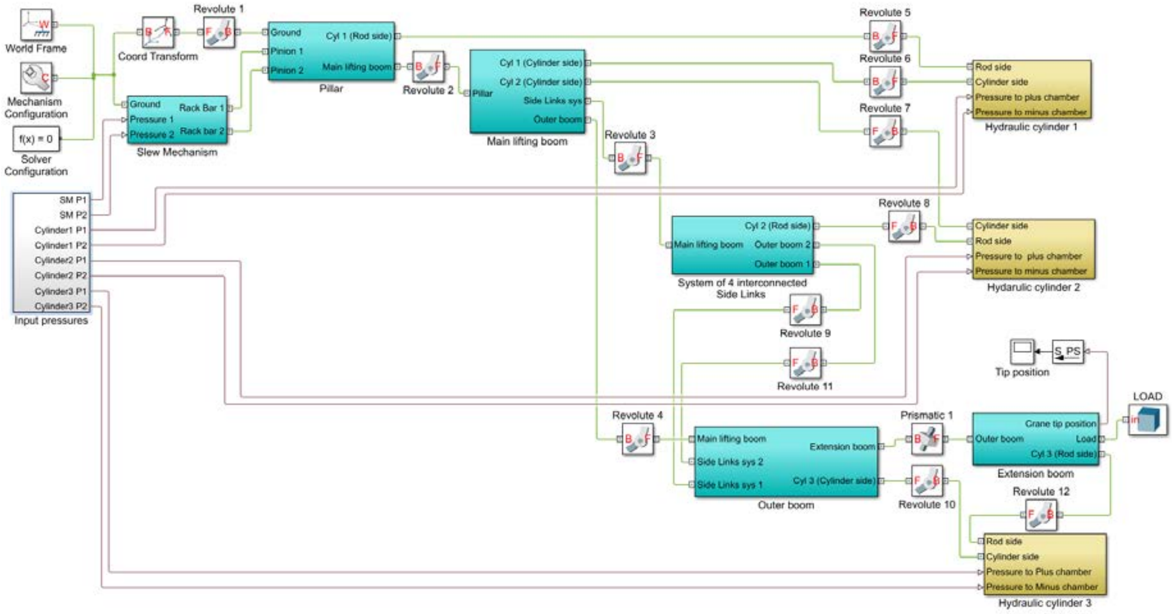

Figure 2. Block diagram of the reference model.

3. Mobile crane model for faster than real-time calculations

Using the same assumptions as in reference model we develop the model with the higher level of abstraction that should be calculated faster but with the accuracy enough for decision making in the task of controlling the crane.

The model of the crane consists of two parts: the dynamic model and the kinematic model. The kinematic model is quite simple and utilises the techniques traditionally used in multibody simulation[5]. The crane is represented as a set of rigid bodies interconnected through the revolute and prismatic joints. The numbering of the joints is indicated in the figure 3.

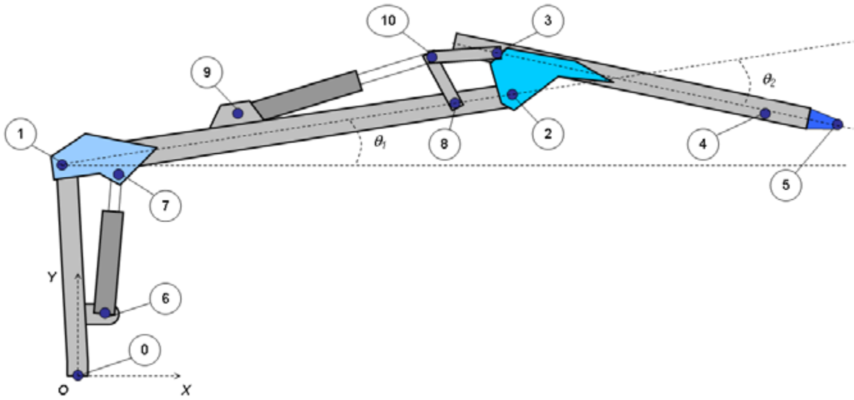

Figure 3. The numbering of the joints of the crane used in kinematic model.

The global origin is located at the base of the crane in the joint 0. Every point of the crane in a global space is represented by a 3x1 position vector $r = [x, y, z]^T$. We locate the origins of the local coordinate systems associated with the crane's booms in the points representing the joints between the booms. For example, the origin of the first boom's coordinate system is located in the Joint 1. We use the numbering of joints to enumerate the local coordinate systems of the booms. Therefore, for the points of the first boom we use the local coordinate system associated with the joint 1.
The orientation of the bodies relative to some coordinate system is defined with 3x3 rotation matrix A :

$$A = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where θ is the angle of rotation.

The position of any point of the boom number j can be represented in the local coordinate system associated with the joint number i as follows:

$$r^i = R^j + A^{ij} u^j$$

where r^i is the position vector of the point relative to the joint i, R^j is the position vector of the origin of the local coordinate system associated with the joint j, relative to the joint i, A^{ij} is the rotation matrix of boom j relative to boom i, u^j is the position vector of the point relative to the joint j.

Translation and rotation together can be represented by 4x4 transformation matrix T_{ij} :

$$T_{ij} = \begin{bmatrix} A^{ij} & R^j \\ 0 & 1 \end{bmatrix}$$

Using the transformation matrix the position vector of the point can be represented as follows:

$$r_4^i = T_{ij} u_4^j$$

where $r_4^j = \left[r_x^j, r_y^j, r_z^j, 1\right]^T$ and $u_4^j = \left[u_x^j, u_y^j, u_z^j, 1\right]^T$.

The notation described above allows us to define the transformation matrices between the coordinate systems associated with the joints:

$$T_{01} = \begin{bmatrix} \cos(\theta_1) & -\sin(\theta_1) & 0 & R_x^{Jp1} \\ \sin(\theta_1) & \cos(\theta_1) & 0 & R_y^{Jp1} \\ 0 & 0 & 1 & R_z^{Jp1} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad T_{12} = \begin{bmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 & r_x^{Jp2} \\ \sin(\theta_2) & \cos(\theta_2) & 0 & r_y^{Jp2} \\ 0 & 0 & 1 & r_z^{Jp2} \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$T_{24} = \begin{bmatrix} 1 & 0 & 0 & r_x^{Jp4} \\ 0 & 1 & 0 & r_y^{Jp4} \\ 0 & 0 & 1 & r_z^{Jp4} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where $R^{Jp1} = \left[R_x^{Jp1}, R_y^{Jp1}, R_z^{Jp1}\right]$ is the global position vector of the joint 1, $r^{Jp2} = \left[r_x^{Jp2}, r_y^{Jp2}, r_z^{Jp2}\right]$ is the position vector of the joint 2 in the coordinate system associated with the joint 1 and $r^{Jp4} = \left[r_x^{Jp4}, r_y^{Jp4}, r_z^{Jp4}\right]$ is the position vector of the joint 4 in the coordinate system associated with the joint 2.

Using these matrices it is easy to calculate the global position vector of any point of the crane. For example the global position vectors of the joint 2 and joint 4 are calculated as follows:

$$R^{Jp2} = T_{01} \cdot T_{12} \cdot \tilde{Z}, \qquad R^{Jp4} = T_{01} \cdot T_{12} \cdot T_{24} \cdot \tilde{Z}$$

where $\tilde{Z} = [0,0,0,1]^T$.

The angle θ_1 can be calculated from the stroke of the first cylinder:

$$\theta_1 = \varepsilon_1 + a\cos\left(\frac{L_{16}^2 + L_{17}^2 - s_1^2}{2 \cdot L_{16} \cdot L_{17}}\right) + \varepsilon_2 - \frac{\pi}{2}$$

where ε_1 is the constant angle between the axis *OY* and the line from joint 6 to joint 1, L_{16} and L_{17} are the distances between the joint 1 and joints 6 and 7, s_1 is the stroke of the cylinder 1 and ε_2 is the angle between the line from joint 7 to joint 1 and the axis *OX* in the position corresponding to such cylinder stroke s_1 that the first boom is horizontal.

The angle θ_2 is calculated from the stroke of the second cylinder and four-bar mechanism that moves the second boom:

$$\theta_2 = 2 \cdot a\tan\left(\frac{-B - \sqrt{B^2 - 4 \cdot A \cdot C}}{2 \cdot A}\right) - (\pi - \theta_{128} - \theta_{235})$$

where

$$A = \cos(\theta_{2810}) - \frac{L_{82}}{L_{810}} - \frac{L_{82}}{L_{32}} \cdot \cos(\theta_{2810}) + \frac{L_{810}^2 - L_{103}^2 + L_{32}^2 + L_{82}^2}{2 \cdot L_{810} \cdot L_{32}}$$

$$B = -2 \cdot \sin(\theta_{2810})$$

$$C = \frac{L_{82}}{L_{810}} - \left(\frac{L_{82}}{L_{32}} + 1\right) \cdot \cos(\theta_{2810}) + \frac{L_{810}^2 - L_{103}^2 + L_{32}^2 + L_{82}^2}{2 \cdot L_{810} \cdot L_{32}}$$

$$\theta_{2810} = \pi - a\sin\left(\frac{Y_{89}}{L_{89}}\right) - a\cos\left(\frac{L_{89}^2 + L_{810}^2 - s_2^2}{2 \cdot L_{89} \cdot L_{810}}\right) + a\sin\left(\frac{Y_{28}}{L_{28}}\right)$$

L_{NM} isthe length of the line segment between joint *N* and joint *M*, Y_{NM} is the projection of this line segment to the axis *OY* in the coordinate system associated with the joint 1, s_2 is the stroke of the second cylinder. The equations mentioned above could be simplified but they are given in that form for better comprehension of their derivation.

The dynamic model of the crane is built using the iterative Newton-Euler dynamic formulation [6]. This formulation is often used for modelling the dynamics of multiple interconnected bodies that have common joints and form the serial chain like the robotic arm does. The crane booms are considered as bodies connected with each other by revolute or prismatic joints.

Iterative Newton-Euler formulation gives the equations for the torques τ_1 and τ_2 acting to the joint 1 and joint 2 respectively. Equating these torques to the torques created by the cylinders we can derive the differential equations for the angles θ_1 and θ_2 :

$$\ddot{\theta}_2 = \left[\tau_2 - \ddot{\theta}_1 \cdot D - P_{2cm}^x \cdot m_2 \cdot B - P_{2cm}^y \cdot m_2 \cdot C - m_4 \cdot g \cdot \left(c_2 \cdot r_x^{Jp3} + s_2 \cdot r_y^{Jp3}\right)\right] \cdot \left(I_2^z + m_2 \cdot \left(\left(P_{2cm}^x\right)^2 + \left(P_{2cm}^y\right)^2\right)\right)^{-1}$$

$$\begin{aligned}
\ddot{\theta}_1 = \Big[& \tau_1 - A \cdot \left(\tau_2 - P_{2cm}^x \cdot m_2 \cdot B - P_{2cm}^y \cdot m_2 \cdot C - m_4 \cdot g \cdot \left(c_2 \cdot r_x^{Jp3} + s_2 \cdot r_y^{Jp3}\right)\right) \cdot \left(I_2^z + m_2 \cdot \left(\left(P_{2cm}^x\right)^2 + \left(P_{2cm}^y\right)^2\right)\right)^{-1} \\
& - \tau_2 + m_1 g\left(c_1 P_{1cm}^x + s_1 P_{1cm}^y\right) + m_2\left(s_1 r_x^{Jp2} - c_1 r_y^{Jp2}\right) \cdot \left(\left(\dot{\theta}_1 + \dot{\theta}_2\right)^2 P_{2cm}^x + \left(\dot{\theta}_1\right)^2 \cdot \left(c_2 r_x^{Jp2} + s_2 r_y^{Jp2}\right) - g\left(c_2 s_1 + c_1 s_2\right)\right) \\
& - m_4 g\left(s_1 s_2 r_x^{Jp2} - c_1 s_2 r_y^{Jp2} - c_2\left(c_1 r_x^{Jp2} + s_1 r_y^{Jp2}\right)\right) \\
& + m_2\left(c_1 r_x^{Jp2} + s_1 r_y^{Jp2}\right) \cdot \left(\left(\dot{\theta}_1 + \dot{\theta}_2\right)^2 P_{2cm}^y + \left(\dot{\theta}_1\right)^2 \cdot \left(c_2 r_y^{Jp2} - s_2 r_x^{Jp2}\right) + g\left(s_2 s_1 - c_2 c_1\right)\right)\Big]
\end{aligned}$$

$$\cdot\left[M - A\cdot D\cdot\left(I_2^z + m_2\cdot\left(\left(P_{2cm}^x\right)^2 + \left(P_{2cm}^y\right)^2\right)\right)^{-1}\right]$$

where

$$A = P_{2cm}^y\cdot m_2\cdot\left(c_1\cdot r_y^{Jp2} - s_1\cdot r_x^{Jp2}\right) + P_{2cm}^x\cdot m_2\cdot\left(c_1\cdot r_x^{Jp2} + s_1\cdot r_y^{Jp2}\right)$$

$$B = \left(\dot\theta_1\right)^2\cdot\left(s_2 r_x^{Jp2} - c_2 r_y^{Jp2}\right) - g\left(s_2 s_1 - c_2 c_1\right)$$

$$C = \left(\dot\theta_1\right)^2\cdot\left(c_2 r_x^{Jp2} + s_2 r_y^{Jp2}\right) - g\left(c_2 s_1 + s_2 c_1\right)$$

$$D = I_2^z + m_2\cdot\left(\left(P_{2cm}^x\right)^2 + \left(P_{2cm}^y\right)^2\right) + P_{2cm}^x\cdot m_2\cdot\left(s_2\cdot r_y^{Jp2} + c_2\cdot r_x^{Jp2}\right) + P_{2cm}^y\cdot m_2\cdot\left(c_2\cdot r_y^{Jp2} - s_2\cdot r_x^{Jp2}\right)$$

$$M = I_1^z + m_1\cdot\left(\left(P_{1cm}^x\right)^2 + \left(P_{1cm}^y\right)^2\right) - r_x^{Jp2}\cdot m_2\cdot\left(s_1\cdot P_{2cm}^y + s_1 c_2\cdot r_y^{Jp2} - s_1 s_2\cdot r_x^{Jp2}\right)$$
$$+ r_y^{Jp2}\cdot m_2\cdot\left(c_1\cdot P_{2cm}^y + c_1 c_2\cdot r_y^{Jp2} - c_1 s_2\cdot r_x^{Jp2}\right) + m_2\cdot\left(c_1 r_x^{Jp2} + s_1 r_y^{Jp2}\right)\cdot\left(P_{2cm}^x + s_2\cdot r_y^{Jp2} + c_2\cdot r_x^{Jp2}\right)$$

I_N is the inertia tensor of the boom *N* and $I_N^z = I_N(3;3)$, m_1 is the mass of the boom 1, m_2 is the mass of the boom 2, m_4 is the mass of the load, $c_1 = \cos(\theta_1)$, $s_1 = \sin(\theta_1)$, $c_2 = \cos(\theta_2)$, $s_2 = \sin(\theta_2)$, P_{Ncm}^x and P_{Ncm}^y are projections of the center of mass of the boom *N* to the axes *OX* and *OY* in the coordinate system associated with joint *N-1*, g is the gravity. Inertia tensors and coordinates of the centers of mass in the local coordinate systems of the booms are taken as constants from the reference model.

τ_1 and τ_2 arethe torques being applied to the joint 1 and joint 2 respectively. They are calculated from the forces produced by the cylinders. We use pressure in the cylinder on the rod side and on the blind side and the geometry of the cylinder as the input parameters to calculate the cylinder force:

$$F_c = p_1 A_1 - p_2 A_2 - F_\mu$$

where p_N and A_N are the pressure and the area on both sides of the piston, F_μ is the friction force.

The Runge-Kutta fourth-order method is used to solve the system of differential equations with the following initial conditions:

$$\ddot\theta_1(t_0) = \dot\theta_1(t_0) = 0, \quad \ddot\theta_2(t_0) = \dot\theta_2(t_0) = 0$$

$$\theta_1(t_0) = f_1(s_1), \quad \theta_2(t_0) = f_2(s_2)$$

where $f_1(s_1)$ and $f_2(s_2)$ are the functions presented above that calculate angles of booms from the initial strokes of the cylinders.

4. Experiments

The results of simulation with the model described above were compared with the results of reference model. The faster than real-time model was implemented as C program, compiled and run on the personal computer comprising 2.26GHz Intel(R) Core(TM) 2 Duo CPU and 4 Gb of RAM. Figure 4 shows the trajectory of the boom tip as a result of the movement simulation with the maximum force that can be produced by the first cylinder $F_c = 137.445$ kN, when the pressure drop is $p_1 - p_2 = 175$ bar. The second cylinder remains static during the movement and holds its initial position. The mass of the load is $m_4 = 200$ kg. The simulated time period is $\Delta T = 2$ s.

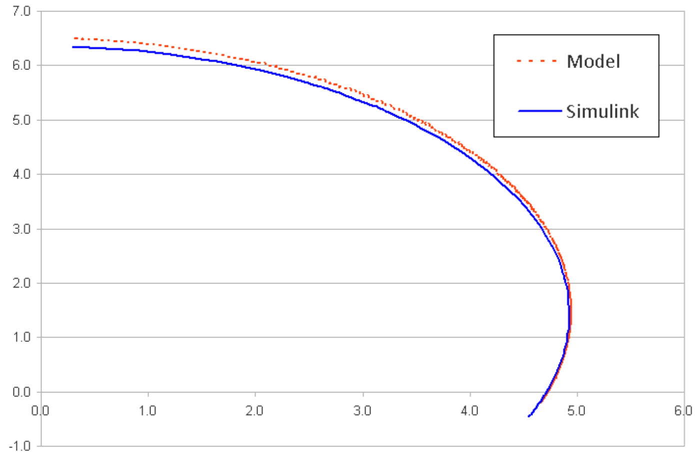

Figure 4. The trajectory of the boom tip simulated with two models.

Figure 4 shows that the crane moves from its initial position to the upper edge position in two seconds. It is unlikely that in reality the crane is operated with the small load and full cylinder pressure but this example demonstrates that small mobile cranes can move relatively fast.

The duration of the program execution for the simulation of 2 seconds of crane's movement is 0.12 seconds that demonstrates its applicability for faster than real-time calculations. The program uses 2500 bytes of memory for its data, the size of the executable file is around 100 kbytes and its exact value depends on the target platform. These parameters of the program make it suitable for the modern embedded systems but the execution time will depend on the CPU capabilities. Nevertheless low memory requirements of the program provide the possibility of its fine customization for the target platform and even hardware implementation.

5. Conclusions and future work

Experimental results show that the proposed simplified model can estimate the movement of the crane. The accuracy of movement prediction depends on the complexity of the model. The proposed simplifications of the model provide the accuracy that is enough for the boom's trajectory prediction. The simplified model can be applied for a wide range of hydraulic actuated mobile cranes with two rotational booms.

The interpretation of the prediction as well as the input parameters of the model should be discussed. As the operation of the mobile crane is a dynamic process, the results of movement prediction should be continuously updated and presented to the operator. These results could be in the form of depicting the position of the crane in the nearest future on some display. Taking into account the possible fast movement of the crane the operator can not be distracted from the view of the real crane and the load. That is why the display should be placed on the operator's head in order to combine the view of the real crane and the calculated future position. Such displays are used for example in the virtual reality (VR) helmets or glasses. At the moment we do not consider the time needed for real-time image generation and display using VR. Alternative solution could be to prohibit the movement of the crane in the case when the simulation predicts the collision. The operator should be notified of this prohibition by some sound or light signal. This kind of signalization is not time consuming and can be executed very quickly. As such behaviour can be unsuitable for some experienced or rapid operators we assume it to be reasonable as it accustoms the operator to more slow and accurate manner of control.

Another question is the input parameters for the model. In the experiments we used the pressure in the cylinders as the input for the forces and torques calculation. It could be better to consider the input signal from the control device used by the operator. The time needed for the interpretation of this signal depends on the control device and should be added to the total simulation time.

Experiments should be made with the real cranes in order to explore different kinds of controllers and to propose the suitable solution for the most popular controllers and hydraulic systems of the cranes.

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