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INTEGRATION OF MODELING IN SOLIDWORKS AND MATLAB/SIMULINK ENVIRONMENTS

In the paper, the authors present construction stages of simulation models worked out using SolidWorks and Matlab/Simulink environments. As examples of simulation models, a laboratory truck crane and a forest crane have been shown. These models allow for visualization of movements, tracking of the trajectory, velocity and acceleration of any point of the system.

1. Introduction

Current technological development has caused an increase in customers' requirements as for designed products. Different conditions and competition on the market mean that new products must be characterized by high quality and functionality. This situation forces engineers to design machines which are characterized by great flexibility and a variety of applications. However, the construction of prototypes of all kinds of devices, which are subjected to experimental research, is impossible because of both economy and time. Therefore, modeling problem [1, 2] is useful and it plays a fundamental role in the design stage of a new structure as well as during the modification of an existing construction. The development of software used to computer-aided design causes that the geometrical models of objects not only can be built, but also one can perform kinematic, dynamic, and strength analysis on the basis of these models in the professional CAD system. However, it is complicated or even impossible to add the control in these applications. Therefore, very often modeling of control systems is performed in Matlab environment with Simulink module [3-6]. Other alternative, but rarely used method of visualization and control of movements of the working machines

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[7, 8], may be the Python programming language with appropriate libraries [9]. However, in this case, the preparation of simulation models is much more laborious and requires programming skills in Python. Matlab is intended to solve complex mathematical problems and generate a graphical visualization of the results. Its scope includes various fields of science and technology. Matlab also provides numerous extensions (toolboxes), among them support for neural networks or optimization problems. One of the extensions is the SimMechanics Toolbox which facilitates the creation of kinematic chains, simulation of their dynamics and visualization of results. Simulink is a tool that allows defining the structure of the control system of mechanisms of the created models and displaying their simulation with complete control during a specified working cycle. This module makes it possible to create, in the graphical window, the structure of the control system which is built of various types of blocks representing dynamic objects, signal sources and measuring instruments. By defined objects, the software can refer to variables existing in memory and available in Matlab.

In the paper, the authors present a course of simulation research carried out on the models elaborated with the use of SolidWorks [10, 11] and Matlab/Simulink.

2. Construction of simulation model

The simulation model is built in stages, that is, at first solid, surface, or hybrid model is created in one of the CAD program. SolidWorks, Pro/Engineer and Autodesk Inventor applications work preferably with the Matlab/Simulink environment.

An assembly of elements can be used solely for simulation studies because in such cases there exists an interaction between individual parts, which in turn makes it possible to introduce the control system and perform motion analysis. Therefore, each created simulation model is an assembly of many individual parts or sub-assemblies. For instance, the sample CAD model presented in Figure 1 consists of: 3 assemblies and 8 parts, but these assemblies include subsequent assemblies or parts, etc.

Building of each part of geometric model in SolidWorks, similar to the ones most currently used for this kind of applications, begins with defining a 2D geometry that creates a solid or a surface after completing one of numerous operations (e.g. extrusion or pocket). Then, based on expansion or modification of the obtained element made by removing or adding material, the creation of parts is continued. The majority of CAD systems offer normalized elements that can be used to build assemblies. The product that is the result of the final assembly of components has a permanent link to the
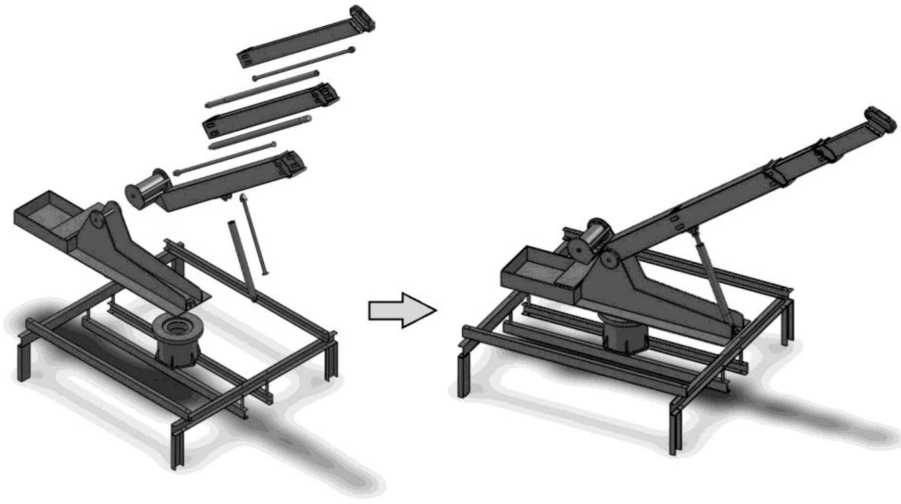
Fig. 1. Sample CAD model (model of laboratory truck crane)

individual part files, which means that changes made in one of the files are automatically ascribed to the linked files, respectively. The product doesn't have its own geometry, instead, it consists of a set of links to the parts and constraints that are used to connect these elements.

The constructed geometric models should be parametric, which allows changing dimensions of components and their positions relative to each other in order to do analysis of motion according to the same model.

Geometrical models can be used not only for the construction of the simulation model, but in a very simple way they can be utilized to carry out other types of analysis, such as modal or stress analysis. In this case, the calculation model which takes into account contact connections and boundary conditions should be worked out.

The next stage of building the simulation model is the implementation of the CAD assembly model in Matlab/Simulink environment (Fig. 2).
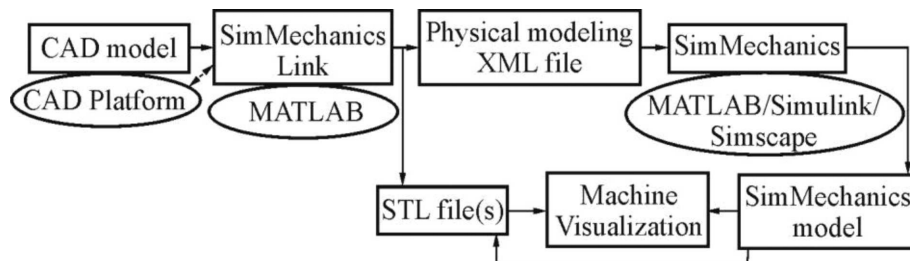

Fig. 2. Implementation process of CAD model in Matlab/Simulink environment

For this purpose, besides previously mentioned CAD software and Mat-lab/Simulink, the SimMechanics Link utility has to be installed and linked to the CAD program [12].

The first step of implementation process is to use the SimMechanics Link exporter to create Physical Modeling XML file that includes information about the mass and inertia of each part of the assembly, definitions of constraints between parts, as well as a set of STL (stereo-lithographic) files for representing surface geometries of the assembly bodies. The second step is import of the received files into the Matlab/Simulink program and generation of a SimMechanics model.

The SimMechanics model, obtained immediately after the implementation, includes a block scheme (Fig. 3) and allows only visualizing mechanism or machine (Fig. 4), without a possibility of carrying out simulation research. Only rarely it is optimal, and does require modifications like removing unnecessary constraints between elements of the model or changing their types.
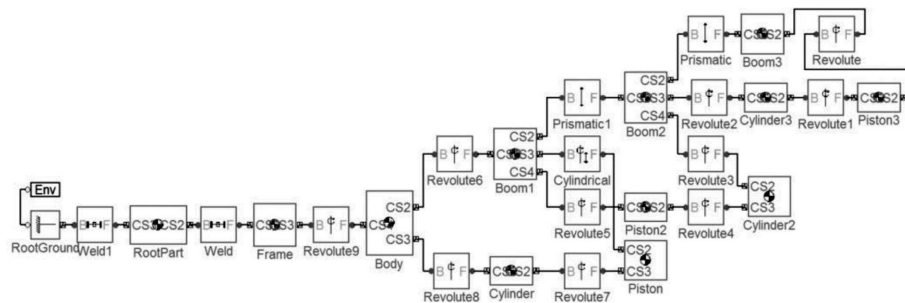
Fig. 3. A sample SimMechanics block diagram

Fig. 4. Visualization of a sample SimMechanics model (model of laboratory truck crane

Simulation tests may be carried out only after the control signals (e.g. kinematic excitations – Fig. 5) and the actuators are added to the model.

In the created SimMechanics model, the control functions are sent to the actuators (Joint Block) with the use of the Joint Actuator block. Joint Block elements, those which occur between the parts of the model as the signal controllers, require movement parameters in the form of position, velocity and acceleration for the prismatic connection (Prismatic Joint) and the angular position, angular velocity and angular acceleration for the rotational connections (Revolute Joint). Because the defined control functions usually describe only velocity, therefore they should be integrated and differentiated through appropriate blocks (Fig. 6) and only at that point they can be sent to the Joint Actuator block in the form of three signals.
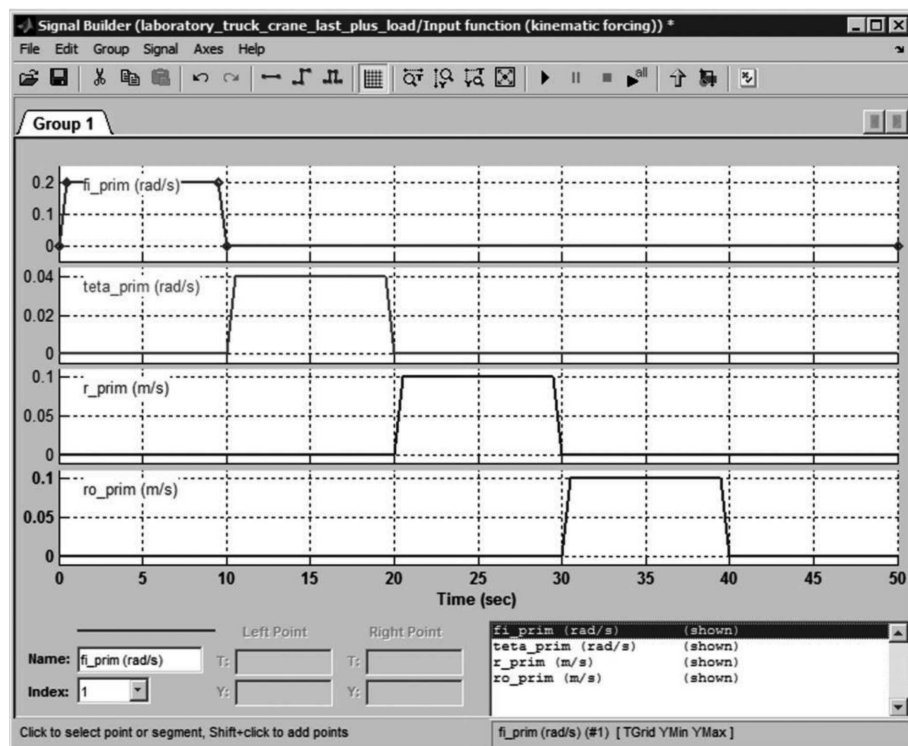

Fig. 5. Sample control signals

In order to improve the transparency of the block diagram, some blocks can be grouped together and transformed into the subsystems, additionally their appearance can be customized by using the process known as masking (the icons of subsystem blocks depict the real objects which they represent).

The modified SimMechanics scheme (Fig. 3) after grouping, masking process and adding the control functions is illustrated in Figure 7.
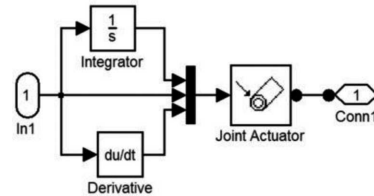
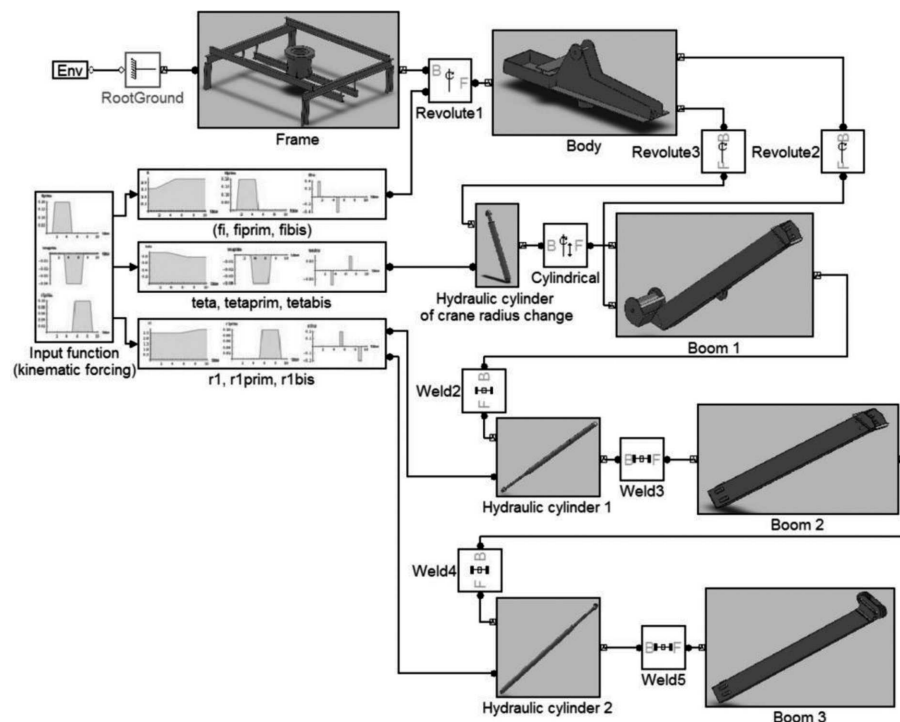Fig. 6. Integration and differentiation of the control signal

Fig. 7. The modified SimMechanics scheme (model of laboratory truck crane)

SimMechanics models allow determining variety of parameters, such as trajectory, velocity, and acceleration of any element of complex system by adding measuring instruments.

Sometimes MATLAB/Simulink environment does not offer elements which appear in many simulation models. In such cases, it is possible to draw up own scripts and functions that can simulate such components.

3. Examples of simulation models

As examples of simulation models worked out with the help of Solid-Works and Matlab/Simulink, the laboratory truck crane and forest crane have been shown.

3.1. The simulation model of laboratory truck crane

The first example of a simulation model worked out according to the course presented in the section 2 illustrates the simulation model of a laboratory truck crane [13]. This model is based on an existing object located at the Institute of Mechanics and Machine Design Foundation of Częstochowa University of Technology [14]. Parametric geometrical model of this object is shown in Figure 1 and it includes, among other things, the platform with the three-member type telescopic boom, the hydraulic cylinder for crane radius change and the construction frame that imitates chassis and is supported on four bearings. All motions of the laboratory truck crane are actuated by hydraulic systems. Linear motions are realized by the hydraulic cylinders, while angular motions by the circulating cam hydraulic motors type SOK. Hydraulic systems ensure independent movements of: two telescopic boom members (second and third), slope of the telescopic boom and angle of rotation of the telescopic boom in the horizontal plane. The SimMechanics block diagram, (Fig. 3), obtained directly after implementation, has been modified by:
– exchange of revolute joints between cylinder and piston rod of all hydraulic actuators for the prismatic joints,
– removal of two prismatic joints between the second and third boom members of telescopic boom; in this case the other blocks ensure the correct action of the system.

Moreover, the SimMechanics model has been supplemented with:
– the Signal Builder block (Fig. 5) used to create the control functions of the laboratory truck crane,
– Joint Actuators which force the movements of individual elements of the laboratory truck crane,
– Body Sensors that read the motion parameters of individual system components,
– Scope blocks for displaying signals generated during simulation.

Besides, some objects were transformed into masked subsystems (Fig. 7). This model allows determination of motion parameters in the form of trajectory, velocity and acceleration of any element of the crane. One of the drawbacks of the presented model is that it does not take into account rope with the lifted load, for the simple reason that in Matlab/Simulink program there is no typical rope element. This problem has been solved by the use of assumptions and relationships presented, among other things, in works [15, 16] where the load is treated as a particle P that is hang on an inextensible rope (which is always lengthened) and fastened at the end of the telescopic boom. An additional moving rectangular coordinate system $\Omega\xi\eta\zeta$ has been

inserted into the existing model; the origin of that system is at the end of the boom (Fig. 8).
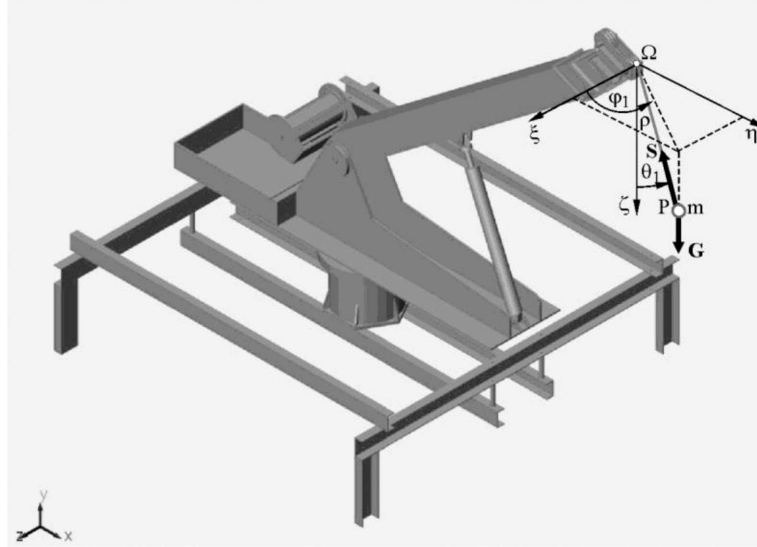

Fig. 8. Scheme of the basic motion of the lifted load

For the above assumptions, the movement of a particle P in the global system, in which mass *m* is concentrated, can be described according to the relationships presented in the cited papers [15, 16] as:

$$\ddot{\xi} = -a_{\Omega Z} + \frac{\xi}{\rho^2} \left[\rho \ddot{\rho} + \dot{\rho}^2 + \xi a_{\Omega Z} + \eta a_{\Omega X} + \zeta \left(a_{\Omega Y} + g \right) - \left(\dot{\xi}^2 + \dot{\eta}^2 + \dot{\zeta}^2 \right) \right], \quad (1)$$

$$\ddot{\eta} = -a_{\Omega X} + \frac{\eta}{\rho^2} \left[\rho \ddot{\rho} + \dot{\rho}^2 + \xi a_{\Omega Z} + \eta a_{\Omega X} + \zeta \left(a_{\Omega Y} + g \right) - \left(\dot{\xi}^2 + \dot{\eta}^2 + \dot{\zeta}^2 \right) \right], \quad (2)$$

$$\ddot{\zeta} = a_{\Omega Y} + g + \frac{\zeta}{\rho^2} \left[\rho \ddot{\rho} + \dot{\rho}^2 + \xi a_{\Omega Z} + \eta a_{\Omega X} + \zeta \left(a_{\Omega Y} + g \right) - \left(\dot{\xi}^2 + \dot{\eta}^2 + \dot{\zeta}^2 \right) \right], \quad (3)$$

where the components $a_{\Omega X}$, $a_{\Omega Y}$, $a_{\Omega Z}$ are accelerations of the boom end in the global system (which is rigidly connected with the crane frame and its origin is located in the support with the bearing), and their values are obtained directly from the simulation model. The system of motion equations $(1, 2, 3)$ supplemented by the initial conditions:

$$\xi \left(t \right)|_{t=0} = \xi_0, \quad \dot{\xi} \left(t \right)\big|_{t=0} = \dot{\xi}_0, \quad (4)$$

$$\eta \left(t \right)|_{t=0} = \eta_0, \quad \dot{\eta} \left(t \right)|_{t=0} = \dot{\eta}_0, \quad (5)$$

$$\zeta \left(t \right)|_{t=0} = \zeta_0, \quad \dot{\zeta} \left(t \right)\big|_{t=0} = \dot{\zeta}_0 \quad (6)$$

constitutes the initial problem of load movement. However, before the initial problem is solved with the help of the ode45 function available in Matlab/Simulink, the above equations must be entered in the form of scripts and functions using Matlab Function object into the SimMechanics model of the existing laboratory truck crane and, at the same time, the following elements must be added (Fig. 9):

– Constant block for generating initial length of the rope,
– Integrating and Differentiating Block,
– Workspace Block in which the system response is collected in the form of data tables.
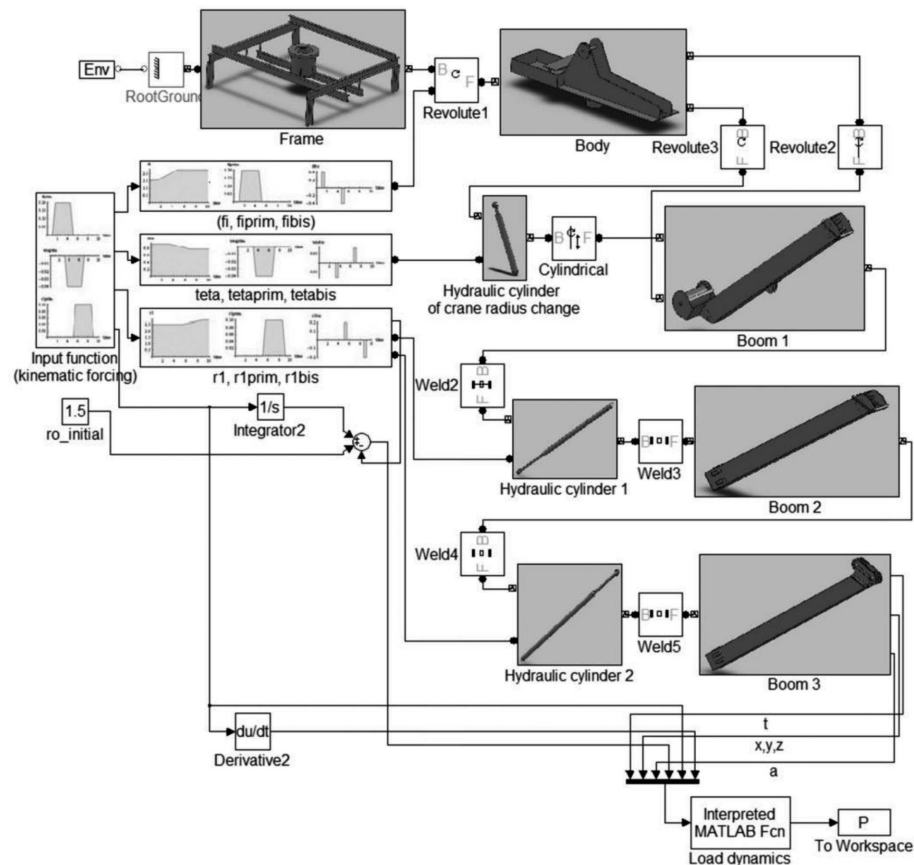

Fig. 9. Modified SimMechanics model

Sample studies on the above simulation model have been carried out for two cases:

– free vibration of a mathematical pendulum moving in spatial motion, with an assumption that the suspension point remains stationary and is tied with the end of the telescopic boom,

– motion of load treated as a response to the kinematic excitations.
In both simulations, the mass of load is equal to 50 kg and the initial length
of the rope (ρ_0) is 1.5 m (length is measured from the end of the boom to
the point of suspension of the load).

For the spatial motion of the mathematical pendulum, the following conditions have been accepted:

$$\xi(t)|_{t=0} = 0, \ \dot{\xi}(t)\big|_{t=0} = 2.63376 \text{ m/s},$$

$$\eta(t)|_{t=0} = 0.5 \text{ m}, \ \dot{\eta}(t)|_{t=0} = 0,$$

$$\zeta(t)|_{t=0} = 1.41421 \text{ m}, \ \dot{\zeta}(t)\big|_{t=0} = 0.$$

In Figure 10, there is shown a response of the system in the form of projections of load motion trajectory on the lifted (10a) and the rotary plane
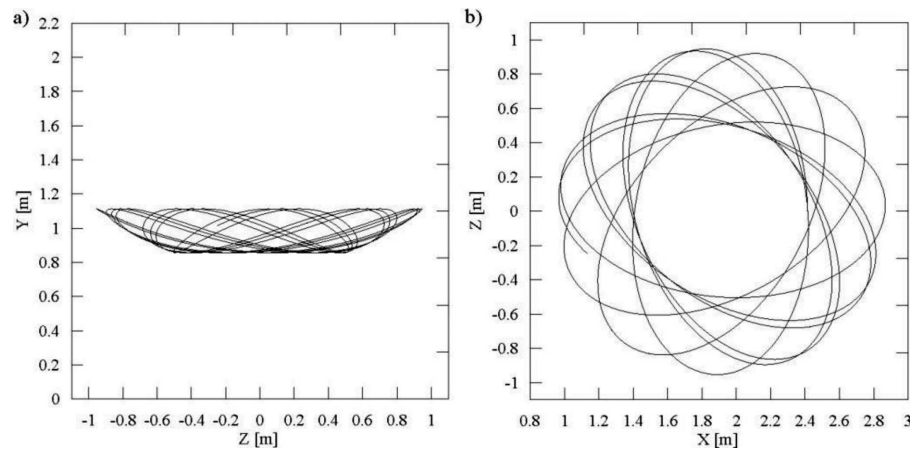(10b).

Fig. 10. Projection of load motion trajectory on the lifted (a) and rotary plane (b)

For the case of solution of the initial conditions under the influence
of kinematic excitations, the movement began from zero initial conditions,
except for $\eta(t)|_{t=0} = 0.5$ m, $\zeta(t)|_{t=0} = \rho_0$. The motion of lifted load was
considered for the time equal 50 s. For the first 40 s, this motion was forced
by the controls (Fig. 5) and, after their action ceased, for the next 10 s free
oscillations of the lifted load were observed. The assumed motion sequences
were directly connected with the working movements of the laboratory truck
crane and they resulted from: control of rotation of platform (fi_prim), control
of the boom inclination angle (teta_prim), control of the rope length which
depends on the rope motion forced by the winch (ro_prim) and, finally, from
the changes in the boom length (r_prim). All control functions were trapezoid
pulses and included start-up, steady and braking movements.

The system response to the taken kinematic excitations has been obtained in the form of animation of motion of the whole system in the SimMechanics Visualization window and in the form of projections of the lifted load motion trajectory on the lifted (Fig. 11a,b) and rotary planes (Fig. 11c).
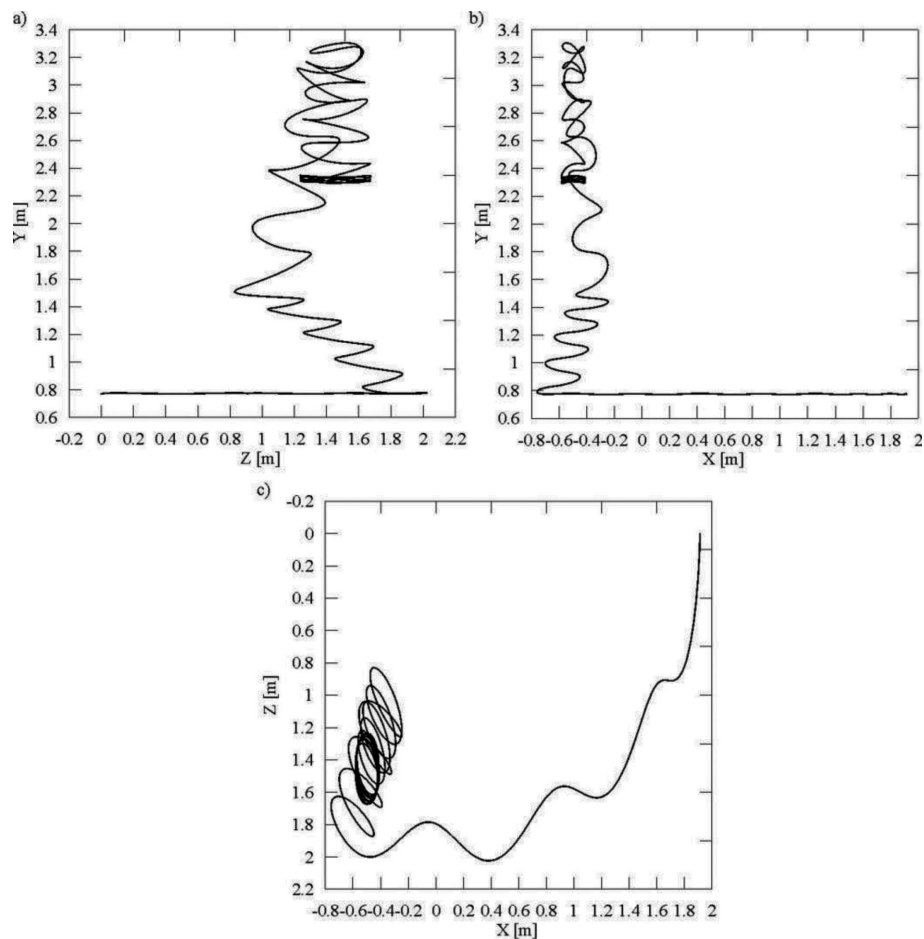

Fig. 11. Projection of the lifted load motion trajectory on the lifted (a, b) and rotary planes (c)

3.2. The simulation model of the forest crane

The second simulation model [17, 18] concerns research on forest crane HIAB LOGLIFT F135 Z79 (Fig. 12), which consists of the following elements:

– the basic member (1),
– the internal arm (2),
– the external arm – two-member telescopic boom (3),

–   the head (4), making up the place for fixing additional working equipment,
–   the hydraulic cylinder (5), used to change the inclination angle of the internal arm,
–   the set of two parallel hydraulic cylinders (6), applied for changing the inclination angle of the external arm,
–   the rotator – the hydraulic mechanism for performing rotational motion (7),
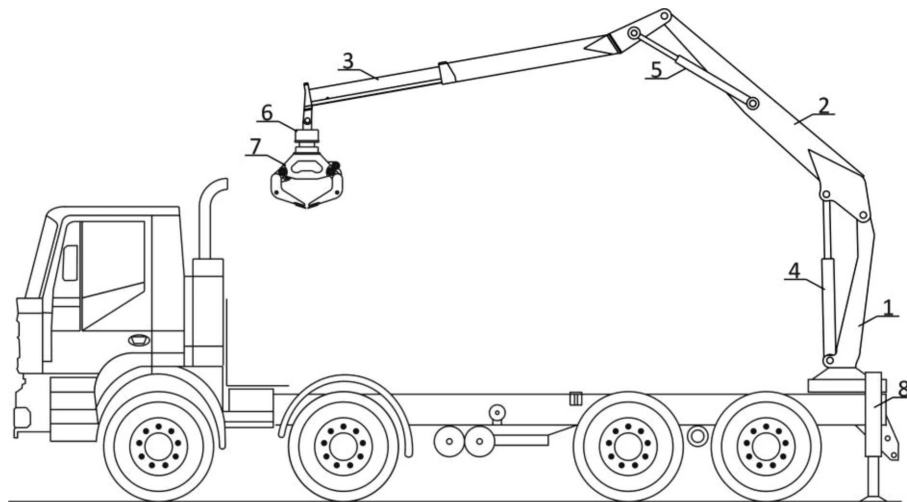–   the manipulator – grab to wood (8),
–   the support system (9).

Fig. 12. The forest crane HIAB LOGLIFT F135 Z79

The worked out CAD model has been converted into the form of a physical model XML and implemented in Matlab/Simulink. Its visualization is shown in Figure 13 and block diagram is illustrated in Figure 14.

The block scheme (Fig. 14) has been supplemented by an appropriate signal source, actuators and measuring instruments, i.e. Signal Builder objects to create time-courses of control signals, Joint Actuators controlling movements of individual crane arm, blocks setting the initial conditions, displacement and velocity sensors, tools for visualization of derived characteristics.

The simulation model was used to carry out a sample simulation of machine cycle. During the working cycle, the machine mechanisms were controlled by time functions, presented in Figure 15, describing the changes of velocity of the following control signals:
–   control of rotation of primary column (Signal 1),
–   control of telescopic boom member (Signal 2),
–   control of deflection of the external arm from the vertical (Signal 3),

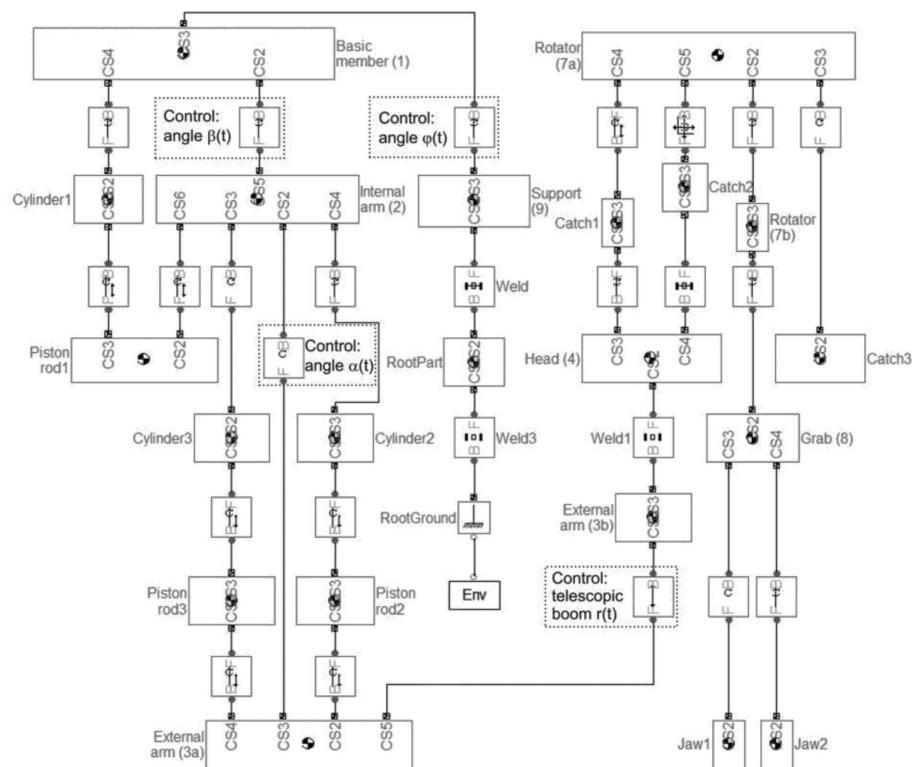Fig. 13. Visualization of the forest crane SimMechanics model

Fig. 14. The forest crane SimMechanics block scheme

– control of deflection of the internal arm from the vertical (Signal 4).

Based on the defined control functions, one obtained the trajectory of the point of attachment of the load, velocity and acceleration components in this movement. The system response is illustrated in Figures 16-18.
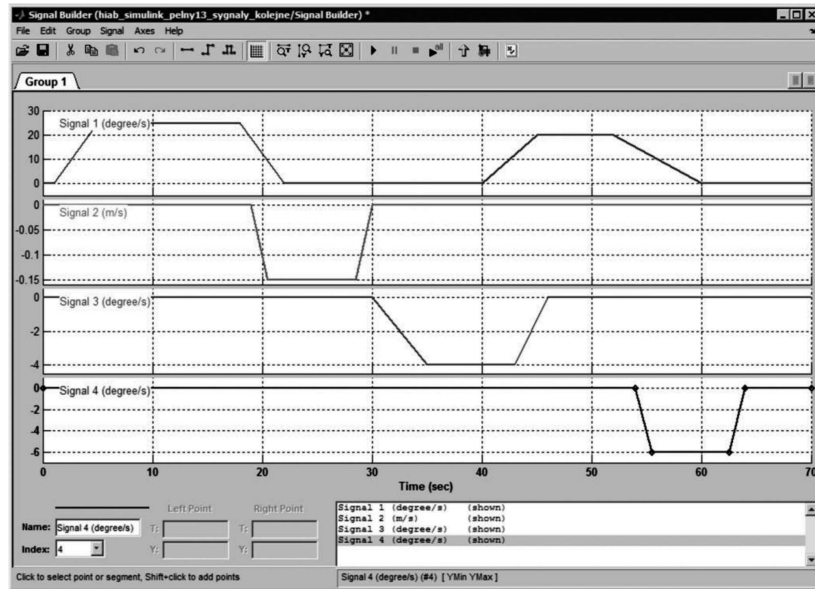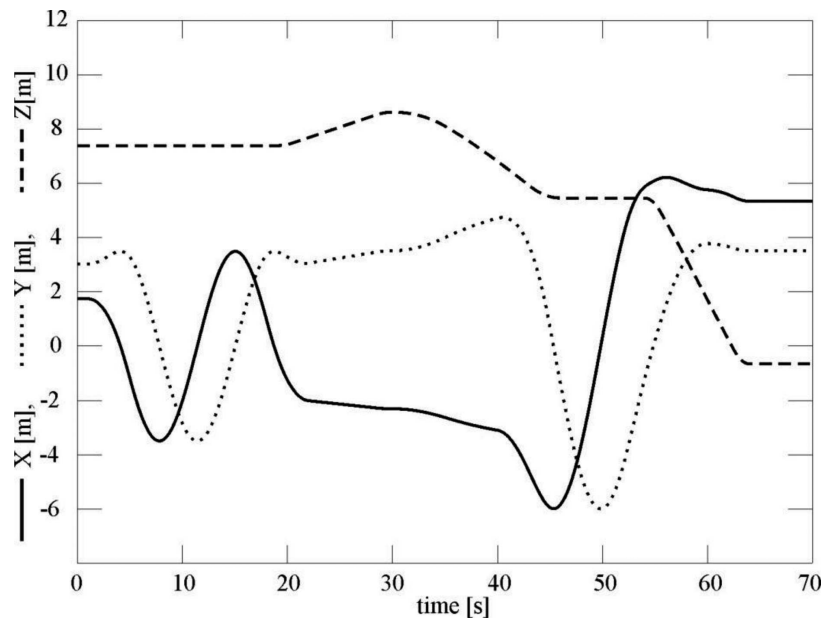
Fig. 15. Control signals

Fig. 16. Position of the boom ends in the global coordinate system

The presented simulation research on forest crane movement have been supported by animation of its motion in the SimMechanics Visualization. It allowed controlling correctness of motion system during a specified cycle.
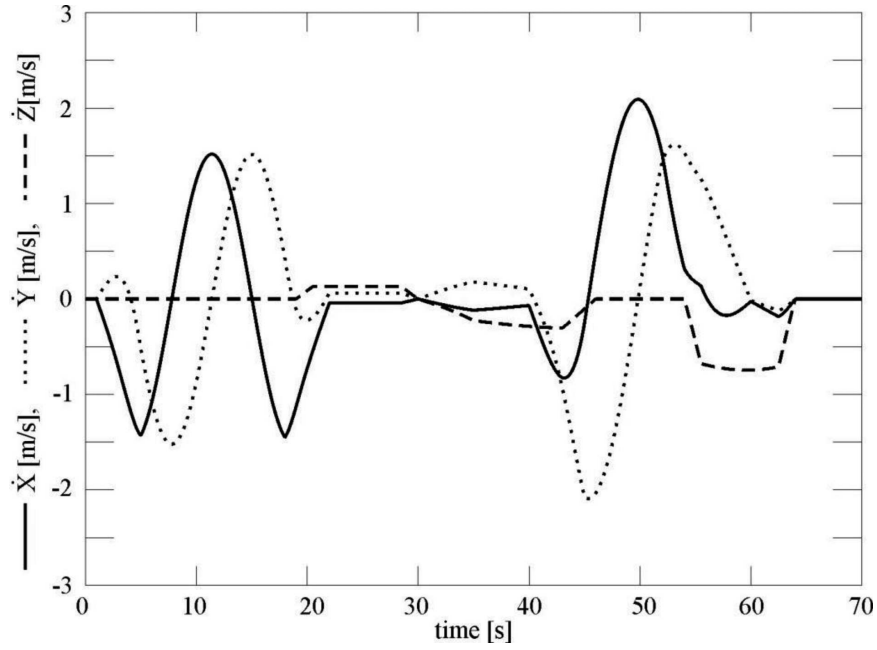
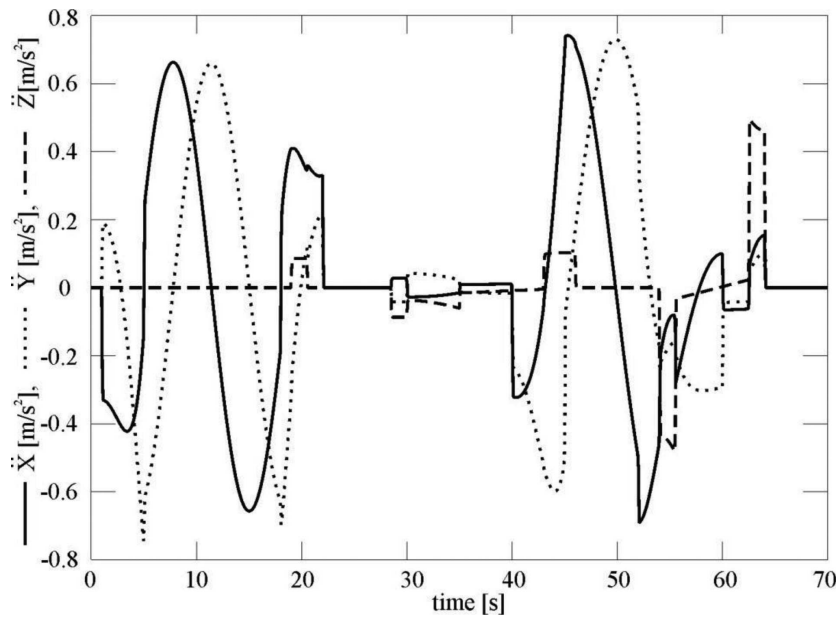Fig. 17. Velocity of the boom ends in the global coordinate system

Fig. 18. Acceleration of the boom ends in the global coordinate system

4. Conclusions

In this paper, we described the integration of SolidWorks and MAT-LAB/Simulink done through the implementation of CAD models, created previously in a SolidWorks program, into the Matlab/Simulink environment. We also presented an example of preparation of simulation models and their application to research on model properties.

As examples of simulation models, the laboratory truck crane [13] and the forest crane [17, 18] have been shown.

In the first case, on the basis of the constructed model, one can carry out simulation research allowing for visualization of movements, tracking of the trajectory, velocity and acceleration of any point of the system and tracking of the lifted load. Tracking of the lifted load was possible through developing the simulation model by adding scripts and functions including derivations of which can be found in works [15,16].

In the second case, the results of research concerning determined movement of forest crane boom have been presented. The results of simulation studies, presented in this paper were confirmed by animations of the forest crane model motion. This model makes it possible to analyze the motion parameters of any boom member or arm of the forest crane and grab with the load.

The presented sample of simulation models can be further developed by:
– replacing the configuration of control operations assumed at the beginning with the movements performed by the operator (user) in real time,
– replacing the kinematic excitations with the help of impact of power transmission and control systems, which makes it possible to get the feedback, which in turn facilitates positioning and reduces fluctuations of the load carried by crane,
– taking into account physical properties (the deformability and damping) of a rope (in the case of the laboratory truck crane),
– replacing particle P (load) with a rigid body (in the case of the laboratory truck crane).

Despite minor imperfections, the Matlab/Simulink environment is one of the most popular and recognizable program for constructing simulation models.

The main advantage of this program is the ability of constructing complex machine simulation models with the use of geometrical models created in other CAD programs without complex mathematical derivations. In this case, the user does not need to possess programming skills.

One of the drawbacks of this method arises from the fact that all imported geometrical models are treated as rigid bodies. However, in the case when the

flexibility of elements should be taken into account, one can attach a block from the Simulink Library Browser (where one exists), as well as write own scripts or/and functions to develop the created model. In such a situation, the capabilities of the constructed mathematical model are limited only by knowledge and skills of the designer.

When flexibility of all elements must be taken into consideration, the CAD models are not used. Yet, all relationships are introduced directly in the form of blocks offered by Matlab/Simulink software, own scripts or functions. An example of this approach is work [19], where the authors worked out a coupled dynamical model of the forest crane and the lifted load taking into account elastic deformations of the boom.

Acknowledgment

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Integracja modelowania w środowiskach Matlab/Simulink i SolidWorks

S t r e s z c z e n i e

W pracy opisano tok postępowania podczas budowy modeli symulacyjnych z wykorzystaniem programu SolidWorks i Matlab/Simulink. Tworzenie modelu symulacyjnego przebiega etapami, to znaczy najpierw opracowywany jest model geometryczny w programie SolidWorks, następnie dzięki możliwości wymiany danych, model CAD jest implementowany w środowisku obliczeniowym Matlab/Simulink. Modele SimMechanics pozwalają na śledzenie wielu parametrów, np. trajektorii, prędkości, czy przyspieszeń dowolnych elementów układu złożonego. W pracy, jako przykłady modeli symulacyjnych opracowanych zgodnie z zaprezentowaną metodą, pokazano modele laboratoryjnego żurawia samochodowego oraz żurawia leśnego. Modele te umożliwiają wizualizację zadanego – za pomocą wymuszeń kinematycznych – cyklu pracy.