Trajectories Planning and Simulation of a Backhoe Manipulator Movement

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Abstract. An excavator is a highly widespread heavy-duty construction machine. The working equipment of the excavator can be thought of as a hydraulic manipulator mounted on a vehicle. To carry out the workflow effectively an operator is to move the bucket teeth along the given path with certain velocity and acceleration under the restrictions imposed by the kinematic parameters of the manipulator and the configuration of the working area. It requires very high skills of the operator. To accurately move the bucket teeth along the desired path the automatic control system can be used. This paper focuses on the excavator manipulator trajectories automatic planning and control. Firstly, the manipulator joints trajectories were obtained to perform digging and levelling operations. Then, a virtual model of the excavator equipment was built based on the MATLAB Multibody to simulate working operations. Finally, digital PID controllers were designed to improve the accuracy of the bucket teeth movement along the path required. As the example, the attached backhoe equipment of the excavator Boreks 2201 is considered.

Keywords: excavator manipulator, MATLAB Multibody model, kinematics, trajectory planning, movement control

1 Introduction

Despite the apparent simplicity of technological processes of road construction, it faces a number of difficulties due to the necessity of increasing the amount of performed works, improving their quality and reducing their cost, which can only be achieved by automation. One of the main reasons that hinder road construction automation is the limited data on the dynamic properties of objects and technological processes. The lack of this information leads to the fact that the hardware and software of road machine control systems are still developed without considering their interaction with each other and with the physical world. And then, after the control system has been developed, it is checked on the models and the impact of various uncertainties is eliminated by the special methods of adjustment. This process is expensive and labour-intensive, and it becomes practically impossible with the complication of the machines [1].

The situation began to change with development of cyber-physical systems (CPS), which are integrations of computation with physical processes [2, 3]. CPS has become an outstanding foundation for creating advanced industrial systems and applications by the integration of innovative features through the Internet of Things (IoT) and Web of Things (WoB) to enable the connection of real physical objects to computing and communication aids [4]. Hence, it is not a coincidence that CPS is one of the main technologies of the fourth industrial revolution, known as Industry 4.0 [4, 5].

As a part of CPS, a model-oriented approach to the design of automatic control systems for complex objects and processes was developed. According to this approach, a simulation model of the control object is created instead of a physical prototype, and it interacts with the physical world using real sensors and actuators [6-8]. It allows passing from simulation models to hybrid ones, which combine both the models of complex objects and the real physical devices, which provides the possibility to verify the concepts and technical solutions without creating physical prototypes and to reduce the number of full-scale tests. However, designing CPS requires more reliable models of physical processes occurring in control systems. The performance of CPS depends on how the model relates to reality.

The most effective software that allows building quite realistic models of complex technical systems, including road machines, are visual modelling tools that combine a graphical form of describing the model and a representation of the results as a 2D or 3D animation. One of the most powerful software providing such possibilities is MATLAB Simscape Multibody™. A valuable advantage of the Simscape Multibody is a CAD translator, which allows creating dynamic models of machines based on their solid models in CAD software like Autodesk Inventor, SolidWorks or Pro / Engineer. It allows relatively simple creating workable models since in CAD it is much easier to establish the correct connections between parts and nodes of a machine. Thus, Simscape Multibody is a perfect tool to investigate such a complex technical system as an excavator working equipment, whereas MATLAB affords an opportunity for connecting a Simscape model with the physical world.

2 Formal problem statement

The aim of the paper is to develop and investigate a control system, which plans the movements of an excavator manipulator in order to move the bucket teeth along a given path and to realize these movements. At this stage of the research, only the kinematics of the excavator manipulator is simulated without the connection of the model with the physical world. As an example, the attached working equipment of the backhoe Boreks 2201 is considered.

3 Literature review

Due to the mentioned advantages, Simscape Multibody is widely used for modelling construction and road machines, in particular, excavators, which are the most common among such machines [9-15]. For instance, the model of an excavator manipulator was built in [10] using Simscape environment to analyse the spatial motion of the working equipment during the workflow.

In [11] the virtual model of the telescopic robotic excavator was built based on the SimMechanics software to simulate levelling and digging operation and to design the excavator manipulator motion controller. The validation of the model was verified experimentally. For this purpose, the hydraulic cylinder displacements on the model and on the real excavator were tracked, and then the x-axis and z-axis coordinate values of the bucket tip was calculated. The experimental results showed good consistency with simulation results. Hence, the SimMechanics model is feasible to study the real operation process.

The Simscape models of an excavator manipulator were also described in [12-14]. These models were used for the excavator boom, arm and bucket hydraulic actuators dynamics analysis and control to minimize vibrations of the excavator bucket during the excavation works. In [15] in order to investigate the skilled operator behaviour, an excavator model with the help of SimMechanics and SimHydraulics was obtained.

This paper continues to research the behaviour of an excavator working equipment with the help of Simscape Multibody models.

4 Model of the excavator manipulator

To study the kinematics and dynamics of the excavator, as well as to test the effectiveness of various control algorithms, a 3D model of Boreks 2201 working equipment was built. For this purpose, the model in Autodesk Inventor 2016 was originally built. Then, the sizes, mass and tensor of the moments of inertia of each element were imported as the mass and inertia of the solid body into Simscape Multibody. The general view of the model is given in Fig. 1.

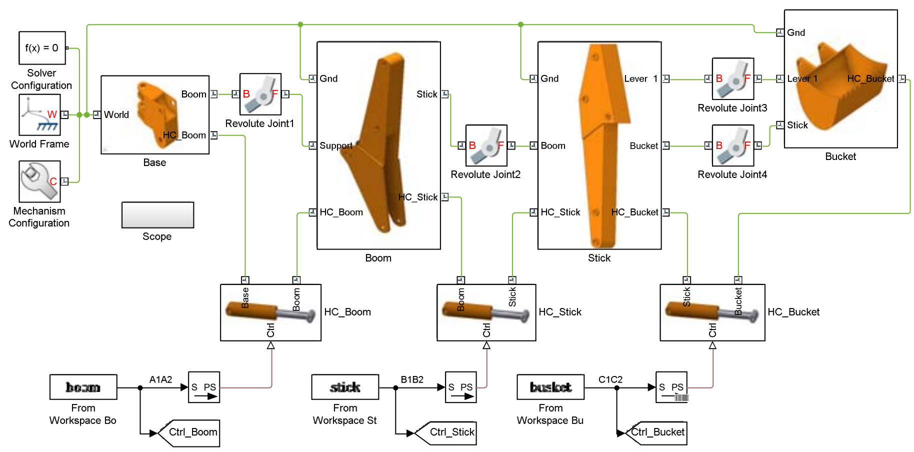

Fig. 1. General view of the excavator manipulator model

A visual representation of the movement of the mechanical part of the excavator manipulator model can be obtained using the built-in visualization function of Sim-Scape (Fig. 2), which allows detecting errors in the model much faster.

Fig. 2. A visual representation of the excavator manipulator model during digging

5 Relation of the joint angles and the displacement of the hydraulic cylinders rods

The ‘boom-stick-bucket’ system of the excavator can be considered as an open kinematic chain, which consists of three serial links connected by rotary joints and driven by hydraulic actuators (Fig. 3). Thus, either joint angles θ_j ($j = 2,3,4$) or displacements L_j of the hydraulic actuators rods can be taken as the generalised coordinates. Here we use the joint angles θ_j ($j = 2,3,4$) as the generalized coordinates since it is more convenient for planning the manipulator trajectories. It should be noted that we do not consider the swing angle θ_1 in this paper, since during digging operation θ_1 remains constant.

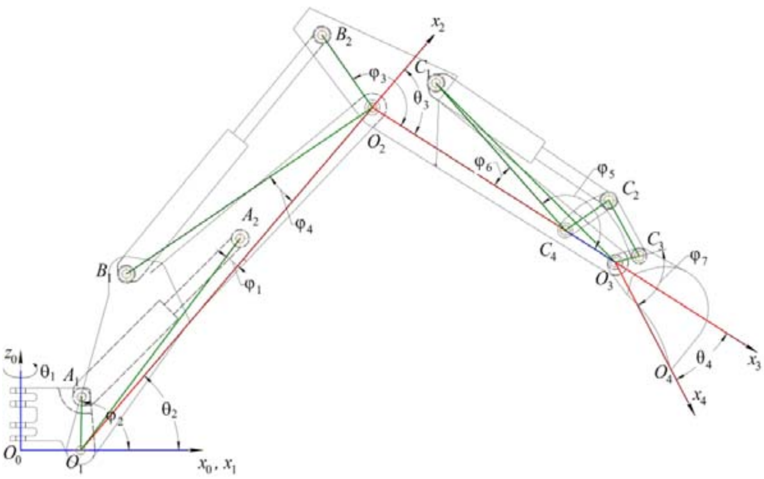

Fig. 3. Coordinate frames of the excavator Boreks 2201 manipulator

Since the change of the joint coordinates θ_j is carried out by displacing L_j the rods of the corresponding hydraulic cylinders, we will find the relations between these variables.

For the boom lengths O_1A_1, O_1A_2 as well as angles φ_1 and φ_2 (Fig. 3) are constant, and their values depend on the features of a particular excavator model. At the same time length A_1A_2 and angle $\angle A_1O_1A_2$ have the variable values. From triangle $A_1O_1A_2$ (Fig. 3) length A_1A_2 is equal to:

$$A_1A_2 = \sqrt{O_1A_1^2 + O_1A_2^2 - 2O_1A_1 \cdot O_1A_2 \cos(A_1O_1A_2)}\ , \tag{1}$$

where angle $\angle A_1O_1A_2$ is

$$\angle A_1O_1A_2 = \varphi_2 - \varphi_1 - \theta_2\ . \tag{2}$$

Similarly, for the stick, the values of angles φ_3, φ_4 and length O_1A_1 are constant, and length B_1B_2 with angle $\angle B_1O_2B_2$ are variable (Fig. 3). Length B_1B_2 of the stick hydro cylinder can be found as:

$$B_1B_2 = \sqrt{O_2B_1^2 + O_2B_2^2 - 2O_2B_1 \cdot O_2B_2 \cos(B_1O_2B_2)}\ , \tag{3}$$

where the value of angle $\angle B_1O_2B_2$ is determined from by following expression:

$$\angle B_1O_2B_2 = \theta_3 - \varphi_3 - \varphi_4 + \pi\ . \tag{4}$$

The relation between length C_1C_2 of the bucket hydro cylinder and the joint angle θ_4 is much more complicated. On the basis of the cosine theorem from triangle $C_3O_3C_4$ (Fig. 3), we find C_3C_4:

$$C_3C_4 = \sqrt{O_3C_3^2 + O_3C_4^2 - 2O_3C_3 \cdot O_3C_4 \cdot \cos(C_3O_3C_4)}\ . \tag{5}$$

Knowing this side angle $\angle O_3C_3C_4$ is:

$$\angle O_3C_3C_4 = \arccos\left(\frac{O_3C_3^2 + C_3C_4^2 - O_3C_4^2}{2O_3C_3 \cdot C_3C_4}\right). \tag{6}$$

From triangle $C_2C_3C_4$ angle $\angle C_2C_3C_4$ can be calculated as:

$$\angle C_2C_3C_4 = \arccos\left(\frac{C_3C_4^2 + C_2C_3^2 - C_2C_4^2}{2C_3C_4 \cdot C_2C_3}\right). \tag{7}$$

Then we can find angle $\angle C_2C_3O_3$. However, there is some difficulty here. At certain value θ_b of the joint angle θ_4, point C_4 lies on the straight line C_1O_3 (Fig. 3). Therefore for the angles $\theta_4 < -\theta_b$ and $\theta_4 \geq \theta_b$ some formulas are different, e.g. if $\theta_4 < \theta_b$:

$$\angle C_3O_3C_4 = \pi + \theta_4 + \varphi_6 + \varphi_7 , \tag{8}$$

and

$$\angle C_2C_3O_3 = \angle C_2C_3C_4 - \angle O_3C_3C_4 . \tag{9}$$

Otherwise, i.e. if $\theta_4 \geq \theta_b$:

$$\angle C_3O_3C_4 = \pi - \theta_4 - \varphi_6 - \varphi_7 , \tag{10}$$

and

$$\angle C_2C_3O_3 = \angle C_2C_3C_4 + \angle O_3C_3C_4 . \tag{11}$$

This fact needs to be taken into account when determining the required length C_1C_2 of the bucket hydro cylinder. From triangle $C_2C_3O_3$ length C_2O_3 is:

$$C_2O_3 = \sqrt{C_3O_3^2 + C_2C_3^2 - 2C_3O_3 \cdot C_2C_3 \cdot \cos(C_2C_3O_3)} . \tag{12}$$

From triangle $C_2O_3C_4$ angle $\angle C_2C_4O_3$ is:

$$\angle C_2C_4O_3 = \arccos\left(\frac{C_2C_4^2 + O_3C_4^2 - C_2O_3^2}{2C_2C_4 \cdot O_3C_4}\right), \tag{13}$$

Angle $\angle O_2C_4O_3$ can be calculated from triangle $O_2C_4O_3$:

$$\angle O_2C_4O_3 = \arccos\left(\frac{O_2C_4^2 + O_3C_4^2 - O_2O_3^2}{2O_2C_4 \cdot O_3C_4}\right), \tag{14}$$

From triangle $C_1C_4O_2$ we find angle $\angle C_1C_4O_2$:

$$\angle C_1C_4O_2 = \arccos\left(\frac{C_1C_4^2 + O_2C_4^2 - C_1O_2^2}{2C_1C_4 \cdot O_2C_4}\right), \tag{15}$$

Then

$$\angle C_1C_4C_2 = 2\pi - \angle C_1C_4O_2 - \angle C_2C_4O_3 - \angle O_2C_4O_3 . \tag{16}$$

Knowing this angle, we find C_1C_2:

$$C_1C_2 = \sqrt{C_1C_4^2 + C_2C_4^2 - 2C_1C_4 \cdot C_2C_4 \cdot \cos(C_1C_4C_2)} . \tag{17}$$

Thus, the resulting equations (1) – (17) establish relations between the values of the joint angles θ_j of the excavator manipulator and lengths A_1A_2, B_1B_2 and C_1C_2 of the corresponding actuators. Knowing the extreme positions of the rods of these cylinders, it is easy to obtain the expressions for their relative displacements L_2, L_3 and L_4.

6 Kinematic control of the excavator manipulator

In general terms, a robotic excavator works as follows. Input information is a desirable path of the edge of the bucket teeth, which can be determined either by an operator or by an on-board computer. Then, by one of the methods given in this section the manipulator trajectories $\theta_j(t)$ planning is performed, which are further converted into the desired displacements of hydro cylinder rods by formulas (1) – (17). Later, the task of realizing these movements under dynamic loads is solved.

In this section, we consider the solution of the problem of determining the change of the joint angles $\theta_j(t)$ at a certain time interval $t\in[t_0, t_f]$, that combines the initial and final configuration and satisfies the given velocities and accelerations constraints at the trajectories endpoints.

In robotics, for trajectories planning, high order interpolation polynomials are widely used, or the trajectory of the link is divided into several segments, each of which interpolates with a polynomial of the lower order [16]. The same methods are also used for robotic excavators [17, 18], although various numerical methods of kinematic control of excavator manipulators are also developed [19-21]. The minimal order polynomial, which satisfies the condition of smoothness and takes into account the constraints on position, velocity and acceleration of the link, is a fifth order polynomial:

$$\theta(t)=a_0+a_1t+a_2t^2+a_3t^3+a_4t^4+a_5t^5\,. \tag{18}$$

The first and second order derivatives of (18) are also smooth polynomials:

$$\dot{\theta}(t)=a_1+2a_2t+3a_3t^2+4a_4t^3+5a_5t^4\,, \tag{19}$$

$$\ddot{\theta}(t)=2a_2+6a_3t+12a_4t^2+20a_5t^3\,. \tag{20}$$

To find the values of coefficients a_k, it is necessary to solve the following system:

$$\begin{pmatrix}\theta_0\\ \dot{\theta}_0\\ \ddot{\theta}_0\\ \theta_f\\ \dot{\theta}_f\\ \ddot{\theta}_f\end{pmatrix}=\begin{pmatrix}1 & t_0 & t_0^2 & t_0^3 & t_0^4 & t_0^5\\ 0 & 1 & 2t_0 & 3t_0^2 & 4t_0^3 & 5t_0^4\\ 0 & 0 & 2 & 6t_0 & 12t_0^2 & 20t_0^3\\ 1 & t_f & t_f^2 & t_f^3 & t_f^4 & t_f^5\\ 0 & 1 & 2t_f & 3t_f^2 & 4t_f^3 & 5t_f^4\\ 0 & 0 & 2 & 6t_f & 12t_f^2 & 20t_f^3\end{pmatrix}\begin{pmatrix}a_0\\ a_1\\ a_2\\ a_3\\ a_4\\ a_5\end{pmatrix}. \tag{21}$$

When splitting trajectories into segments, the so-called Linear Segments with Parabolic Blends (LSPB) is mostly used. It provides a trapezoidal profile of the velocity which imposes a constant acceleration in the start phase, a cruise velocity, and a constant deceleration in the arrival phase. The essence of LSPB is the following. The desired trajectory of every link of the manipulator is divided into three parts. The first part starts from time t_0 to time t_b and is described with a quadratic function. It leads to a gradual increase in velocity. At time t_b, called the blend time, the trajectory changes to a linear function. In the end, at the moment $t_f - t_b$, the trajectory changes again to the quadratic function when the velocity gradually decreases.

In terms of smoothness of accelerations, it is expedient to use the fifth order polynomials for the excavator manipulator trajectories planning, while the LSPB provides a greater speed of work operations execution. In this case, however, the laws of velocities and acceleration change do not satisfy the constraints in smoothness, which leads to jerks of working equipment.

In some cases, for example, at levelling, it is necessary to ensure the movement of the bucket teeth along the straight line in Cartesian space. In this case it is better to plan the trajectories directly in Cartesian space. In such a case, the initial and final points of the path are described by a homogeneous transformation matrix, which establishes a relationship between the bucket coordinate frame and the world coordinate frame. Then the values of the joint angles θ_j corresponding to these points are calculated using the manipulator inverse kinematics. Further, the trajectories between these points are interpolated in the joint space [16].

The described methods have been used for the trajectories planning of the Boreks 2201 manipulator. Two types of the bucket teeth path have been considered (Fig. 7):

– a path in the form of a parabolic line that simulates the movement of the bucket during the digging operation;

– a straight line path, that simulates the levelling operation.

As the boundary conditions, it has been assumed, that velocities v_0, v_f and accelerations a_0, a_f, of the manipulator links at the initial and final points of the path should be zero.

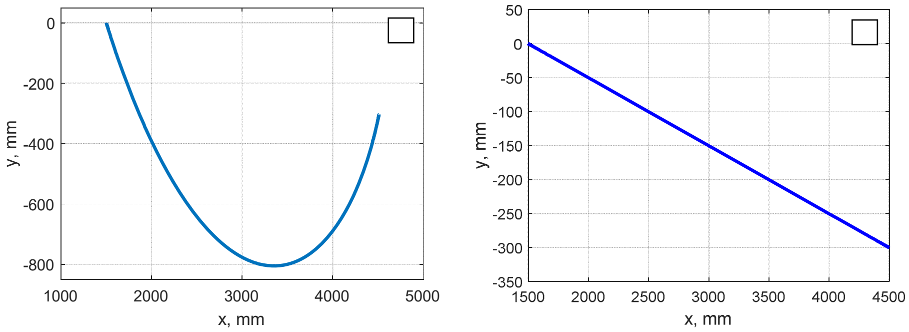

Fig. 4. Bucket teeth desired trajectories for digging (a) and levelling (b) operations

7 Manipulator movement simulation

7.1 Digging simulation

Determination of joint angles $\theta_j(t)$ ($j = 2,3,4$) changing and, consequently, the rods relative displacements $L_j(t)$, which provide the displacement of the bucket teeth along the parabolic line (Fig. 4a), have been carried out according to the equation (21). The actual displacements $L_j(t)$ of the actuators rods obtained at the model (Fig. 1) are shown in Fig. 5, and their velocities $v_j(t)$ and acceleration $a_j(t)$ are shown in Figs. 6 and 7 accordingly. These figures show that in general, the obtained trajectories meet the requirements of smoothness, which minimizes the overloads in the kinematic chain of the excavator manipulator. The maximum velocities of the rods are 0.32 m/s.

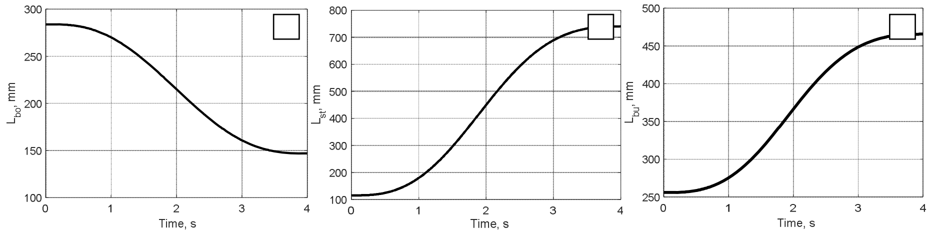

Fig. 5. Estimated displacement of the actuators rods of the boom (*a*), the stick (*b*) and the bucket (*c*) for the parabolic bucket path

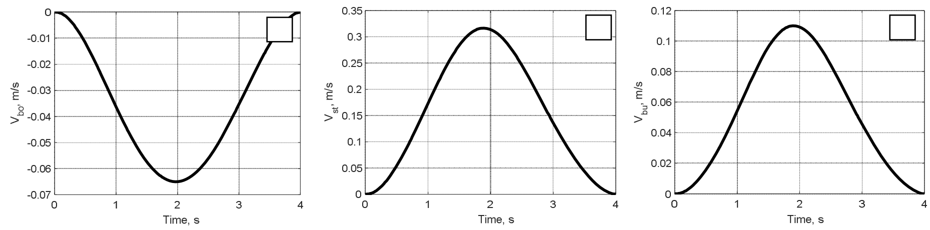

Fig. 6. Velocities of the actuators rods of the boom (*a*), the stick (*b*) and the bucket (*c*)

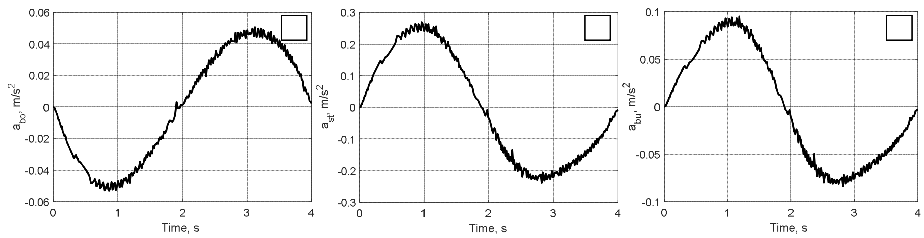

Fig. 7. Accelerations of the actuators rods of the boom (*a*), the stick (*b*) and the bucket (*c*)

Tracking errors of the boom and the bucket actuators rods are insignificant (Fig. 8): 1.3 mm (Fig. 8a) and 2.2 mm (Fig. 8c), respectively. However, the maximum tracking error of the hydraulic cylinder rod of the boom is quite large and modulo greater than 6 mm (Fig. 8b). These errors can be explained by the dynamic properties of the excavator manipulator.

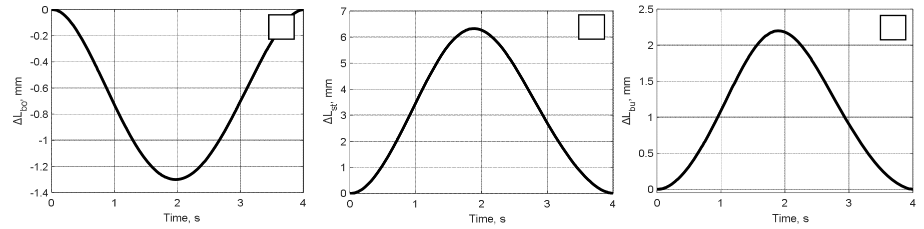

Fig. 8. Tracking errors of the actuators rods of the boom (*a*), the stick (*b*) and the bucket (*c*) for the parabolic bucket path

The presence of these tracking errors leads to some differences in desired and actual paths: the maximum error in the *x*-direction is 33 mm, and in the *y*-direction is 14 mm (Fig. 9). These are the acceptable digging errors for real conditions of excavation.

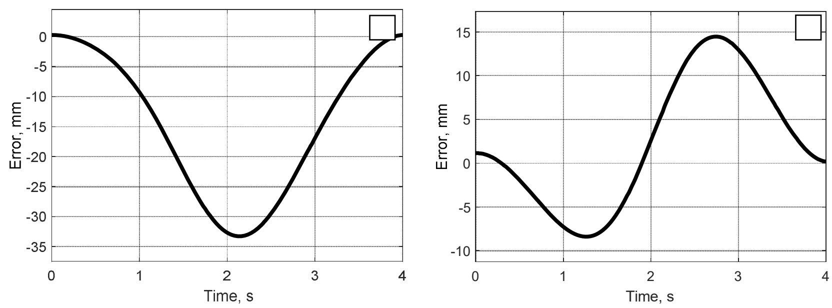

Fig. 9. Digging errors in the *x*-direction *x* (*a*) and in the *y*-direction (*b*)

It should be noted that in this paper only the kinematics of the excavator is considered, so dynamic loads are not taken into account. Obviously, in the presence of digging resistance forces, the digging errors will increase.

7.2 Levelling simulation

Planning of the excavator manipulator motion to move the bucket teeth along a straight line is made in Cartesian space. The obtained laws of the hydraulic cylinder rods displacements are shown in Fig. 10.

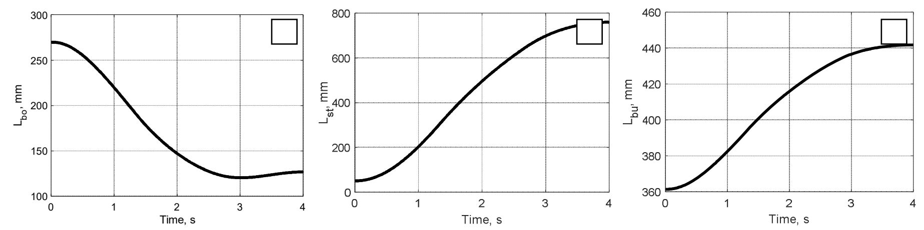

Fig. 10. Displacements of the rods of the boom (*a*), the stick (*b*) and the bucket (*c*) hydraulic cylinders

The velocities and accelerations of the rods are given in Fig. 11 and Fig. 12. The maximum velocity of the rods is 0.33 m/s, which does not exceed the allowed maximum velocity of 0.5 m/s. However, the laws of changing velocities and accelerations are not smooth, so jerks of acceleration can be seen in the graphs.

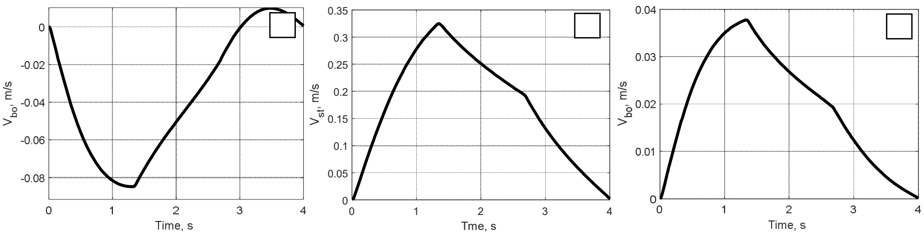

Fig. 11. Velocities of the movements of actuators rods of the boom (*a*), the stick (*b*) and the bucket (*c*) at levelling

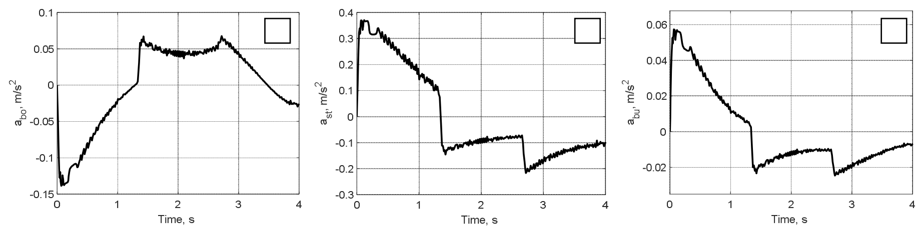

Fig. 12. Accelerations of the movements of actuators rods of the boom (*a*), the stick (*b*) and the bucket (*c*) at levelling

Tracking errors for the rods are shown in Fig.13. From these figures it is evident that, as in the case of the parabolic path, at levelling, the actuator of the stick has the maximum tracking error – about 7 mm.

The errors of the bucket teeth motion along the straight line are illustrated in Fig. 14; it can be seen that the maximum absolute error is 22 mm for the *x*-axis, and 3.2 mm for the *y*-axis. It is also worth to note that the straight line path of the bucket teeth is one of the most difficult paths to perform by an operator [22].

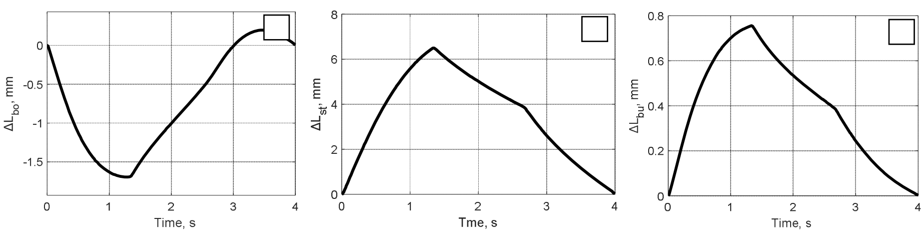

Fig. 13. Tracking errors of the actuators rods of the boom (*a*), the stick (*b*) and the bucket (*c*) for the parabolic bucket path at levelling

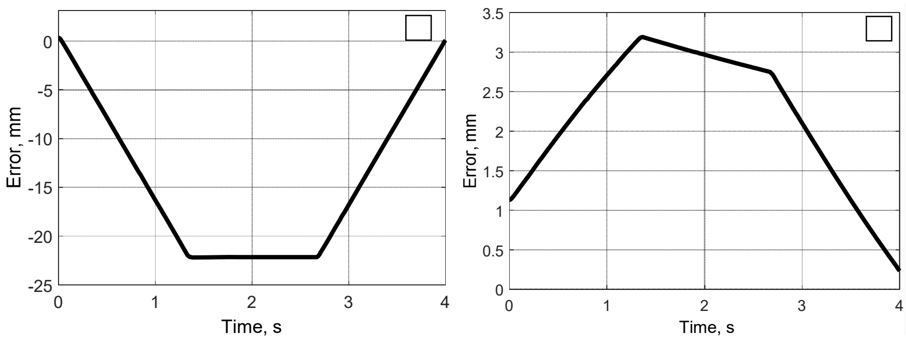

Fig. 14. Levelling errors in the *x*-direction (a) and in the *y*-direction (b)

8 Controller design

To improve the quality of the desired trajectories tracking by the excavator manipulator, the digital PID controllers are designed. The transfer function of the controller is:

$$C(z) = k_p + \frac{k_i T_s}{z-1} + \frac{k_d}{1 + \frac{N T_s}{z-1}}, \tag{22}$$

where k_p, k_i and k_d are the controller proportional, integral and derivative gains respectively; N is the filter coefficient and T_s is the sampling time.

A separate controller is used to control each joint. For this, the 'Controller' subsystem has been added (Fig. 15) to the model shown in Fig. 1. Tuning of the controllers parameters has been performed by means of Simulink Control Design. The sampling time is chosen T_s = 5ms. The results of the controllers tuning are given in Table 1.

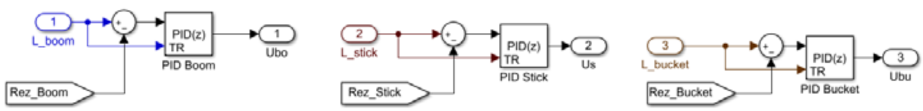

Fig. 15. The subsystem 'Controller' of the Boreks 2201 model

The use of PID controllers allowed reducing displacements errors of the hydraulic cylinders rods significantly. For example, the tracking error of the stick hydraulic cylinder rod when moving along the parabolic path decreased from 6 mm to 3 mm, and along the straight line – from 7 mm to 3 mm. It improved the accuracy of the joint angles execution accordingly, and, consequently, the accuracy of passing the bucket teeth along the given path (Table 1).

Table 1. The controllers parameters and path tracking errors

Controller parameters					Path tracking maximum error, mm			
	k_p	k_i	k_d	N	Parabolic Trajectory		Straight Line	
					x	y	x	y
Boom	4.4	159.7	0.015	337	2	4	2	5
Stick	2.7	119.5	0.009	225	7	2	6	2
Bucket	2.2	106.8	0.007	291	15	6	10	2

We note again that the given results are obtained in ideal conditions, that is, in the absence of external forces that appear, for example, when the bucket interacts with the soil. It should be expected that with the presence of these forces, as well as with the changing weight of the bucket during its loading, there will be more significant deviations between the desired and the actual paths. In order to avoid this, it is necessary to implement the appropriate controllers.

9 Conclusion and future work

Improving efficiency of excavators is inseparably linked with implementation of the working equipment automatic control systems. One of the main tasks of such control systems is to plan and execute such movements of the excavator manipulator links, which ensure the movement of the bucket along the given path.

In order to develop such a control system, in this paper the relationship between the position of hydraulic cylinder rods of the excavator manipulator and its joint angles has been determined. The task of the kinematic control of the excavator manipulator has been solved, that is, determination and provision of such laws for changing the angles of the links joint, their velocities and accelerations, which ensure the movement of the bucket teeth along the desired path in Cartesian space in the presence of constraints. When digging is accomplished, trajectories planning is desirable to perform in the joint space (in this paper we have used a fifth-order polynomial approximant), whereas, the bucket movement along a straight line is better to plan in Cartesian space.

In order to investigate the excavator manipulator movement, the 3D model of the Boreks 2201 manipulator was built in the MATLAB Simscape Multibody software. Experiments with the 3D model have shown that hydraulic actuators perform the desired trajectories with some errors due to the influence of mass-inertial parameters. As a result, the quality of the earthworks is decreasing.

The use of digital PID controllers increased the accuracy of the trajectories tracking by the manipulator links and, therefore, improved the precision of the bucket teeth movement along the desired path up to 67% in the case of the parabolic path and up to 33% in the case of the straight line path.

However, the given results are obtained under the ideal conditions, that is, in the absence of external forces that arise, for example, due to the bucket and the soil interaction. More significant deviations between the desired and actual paths should be expected when these forces are considered, as well as the bucket weight change during its filling. In addition, uncertainties about the manipulator parameters values and the digging resistance forces values could well significantly influence the control system performance. Our future work is related with the study of the excavator manipulator dynamics, taking into account the indicated factors, as well as with a robust controller design to ensure the effective performance of the excavator workflow under the presence of variable and uncertain loads. Furthermore, our future research provides for connecting the model of the excavator manipulator with the physical world by using real-life actuators instead of their models. It should give more reliable data about the control system performance in real conditions.

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