Bulldozer sensing technique for the purpose of automation for bulldozer's workflow

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Abstract –

Recently, global positioning systems - GLONASS and GPS are increasingly used for road construction machines. Often, mobile stations installed on the construction site are used, which increase positioning accuracy, but have a limited range. Providing a signal source to every running machine is very costly. Taking into account the often large length of construction sites, it is laborious to move the mobile station. It is also worth considering the insufficient positioning accuracy of these systems in some areas of the world.

Therefore, in order to implement an effective workflow, it is necessary to develop and apply systems for monitoring and controlling the workflow of a bulldozer based on an alternative approach.

The purpose of the research is to collect data on the parameters of working processes in dynamics to identify the working process of the bulldozer, assess the statistical characteristics of disturbing influences and confirm the mathematical models of the working processes of the bulldozer.

In the article, the authors propose a method for digitizing experimental data based on the provisions of the theory of random processes and digital signal processing. A technique for changing the sampling rate of measured signals while maintaining working signal, used to characterize measured process indicators, analyze dynamics and identify a bulldozer's workflow.

Keywords –

Mechatronic system; Bulldozer blade; Leveling control; Sensing system

1 Introduction

There is a very common laser control system is a high-tech earthmoving installation that allows you to perform work without the usual use of building poles and leveling rods. The use of laser technology, components of the used machinery, and a remote laser transmitter allows the machine control system to obtain accurate information about the terrain, displaying it on the display located in the cab, and, ultimately, setting the blade in the desired position.

A laser transmitter located outside the cab on a tripod emits a thin beam of light that rotates 360 ° to create a slope calculation above the construction site. The cutting edge, located above the surface to be graded, is controlled by a signal sent from an electrically driven tripod that automatically locates the laser receiver within 1.5 mm of the center of the laser beam [1].

The display located in the cab of the bulldozer shows information about the position of the knife blade relative to the ground, at the same time showing where the construction site should be excavated, and where - dumping. The automatic control of the position of the blade allows precise adjustment of the cutting edge. Depending on the content of the correcting signals, the hydraulic double control valve automatically raises or lowers the blade edge, constantly holding it in the desired position, which ensures precise work execution and guarantees an optimal level of labor productivity [2].

The advancement of GLONASS / GPS technology and its use in construction helps to reduce labor requirements and helps heavy equipment operators to complete the work order under the design solution, through careful excavation and filling of soil, it can achieve material cost savings [3].

The system operates as follows: on-board equipment is installed on vehicles, which includes a satellite GLONASS / GPS receiver, a microcontroller, and information collection and transmission facilities. The onboard equipment is used to determine the current coordinates, speed, course, collect information about the status of sensors, control actuators, and signals. All this information is processed specially and transmitted/received to the dispatch center. The accumulated information from the database is used to analyze and generate the necessary reports and logs.

Such a control system is a high-tech machine control system and a dialogue control system that allows you to reach the proper level of earthwork without elevation marks and leveling rails. Digital design inputs, manuals, and instructions in the dozer's automatic blade position control system help you achieve the desired result faster, more efficiently, and economically, with lower costs.

Bulldozers equipped with modern navigation and information systems are mobile mechatronic objects, and they can be integrated into general process of intellectual construction. The integration will provide optimal efficiency of the construction cycle and will ensure lean production process.

On the basis of bulldozer's workflow dynamics modeling and analyses described in a variety of works, we have concluded that the models to describe kinematics and dynamics of its working equipment, hydraulic and transmission features tend to be analytical formulas derived from well-known laws of physics and from information on bulldozer's structure and mechanisms. If some parameters of the workflow are unknown or constantly changing, the models are either statistical tables or empiric dependences summarizing experimental data. The models depict interaction of end-effectors, engines and environment as well as statistic features of bulldozer's complex units.

Application of regulators based on classical control theory is difficult due to the frequent changes in workflow conditions. Thus, it is necessary to develop adapted control systems to eliminate the difficulties described. The system includes both the bulldozer's dynamics modeling and bulldozer's workflow control method to take into consideration the complex non-linear dependencies between workflow parameters and incomplete information on its working conditions changes.

Having reviewed adaptive and intellectual control methods [4, 5], we propose to create an adaptive control system for technological processes to increase efficiency of bulldozer's control in comparison with traditional control methods.

2 Mathematical model to estimating the position of blade cutting edge

Observations [6-8] show that quite often while designing a face its roughness is progressing, reaching a size at which the control over the workflow is lost. In this case, the operator has to align the face deliberately, trying to ensure its "tranquil" profile that allows doing excavation works smoothly, without frequent control system switching and reducing the dozer's operating speed that causes a slowdown and shows inferiorities of the blade control system. Obviously, if the control system operates in the antiphase towards deviations of the tractor frame with sufficient accuracy, the initial face roughness will not evolve and will be gradually cut. One of the most likely causes of the opposite phenomenon observed in practice, is the disparity between the velocity of the dozer V_p and actual conveying speed of the working body V_{ot} required in certain areas S_i of the digging operating cycle, where *i* – is the number of the speed change V_{ot}. Speed ratio depends on the dozer's geometrical dimensions (Fig. 1) and its control system.

Mathematical model of the dozer's movement on a straight line tracking (frame alignment) is built using the Lagrange equations of the 2nd kind, under the assumption that the contribution to the dynamics of the drive gears and a track is small, compared with the contribution of the remaining parts of the dozer.

$$\begin{cases} \dfrac{d}{dt}\left(\dfrac{\partial T}{\partial \dot{x}}\right) - \dfrac{\partial T}{\partial x} = Q_x\,, \\[2ex] \dfrac{d}{dt}\left(\dfrac{\partial T}{\partial \dot{\varphi}}\right) - \dfrac{\partial T}{\partial \varphi} = Q_\varphi\,. \end{cases} \qquad (1)$$

where kinetic energy:

$$T = \frac{1}{2}m_1\dot{x}^2 + \frac{1}{2}m_2\big(\dot{x}^2 + (l_2 l_{c2}\dot{\varphi})^2 + 2\dot{x}l_2 l_{c2}\dot{\varphi}\sin(\varphi)\big) + \frac{1}{2}J_{c2}\dot{\varphi}^2 + \frac{1}{2}\sigma hx\big(\dot{x}^2 + {} + (l_2\dot{\varphi})^2 + 2\dot{x}l_2\dot{\varphi}\sin(\varphi)\big) + \frac{1}{2}\sigma hx i_{rz}^2\dot{\varphi}^2; \qquad (2)$$

generalized forces acting on a dozer:

$$Q_x = -\sigma h g l_2 \sin\varphi + F_{\text{т}} - F_s,$$
$$Q_\varphi = -(m_2 l_{c2} + \sigma x h) g l_2 \cos\varphi + M; \qquad (3)$$

m_1 – tractor mass; m_2 – blade frame mass; σ – soil surface density; $F_{\text{т}}$ machine pulling power; F_s ground cutting resistance; h – depth of the soil cutting; l_{c2} – center of the blade mass; i_{rz} - gyration radius of the dumping soil.

$$m_1\ddot{x} + m_2\ddot{x} + m_2 l_2 l_{c2}\ddot{\varphi}\sin\varphi + m_2 l_2\, l_{c2}\dot{\varphi}^2\cos\varphi + \sigma h\dot{x}^2 + \sigma h x\ddot{x} + \sigma h\dot{x}l_2\dot{\varphi}\sin\varphi + \sigma h x l_2\ddot{\varphi}\sin\varphi + \sigma h x l_2\dot{\varphi}^2\cos\varphi - \frac{1}{2}\sigma h\dot{x}^2 - \frac{1}{2}\sigma h i_{rz}^2\dot{\varphi}^2 - \frac{1}{2}\sigma h(\dot{x}^2 + l_2^2\dot{\varphi}^2 + 2\dot{x}l_2\dot{\varphi}\sin\varphi) = -\sigma h g l_2\sin\varphi + F_{\text{т}} - F_{\text{сопр}}. \qquad (4)$$

$$m_2 l_2^2 l_{c2}^2\ddot{\varphi} + m_2\ddot{x}l_2 l_{c2}\sin\varphi + m_2\dot{x}l_2 l_{c2}\cos\varphi\dot{\varphi} + J_{c2}\ddot{\varphi} + \sigma h\dot{x}l_2^2\dot{\varphi} + \sigma h x l_2^2\ddot{\varphi} + \sigma h\dot{x}l_2\sin\varphi + \sigma h x l_2\cos\varphi\dot{\varphi} + \sigma h\dot{x}i_{rz}^2\dot{\varphi} + \sigma h x i_{rz}^2\ddot{\varphi} - m_2\dot{x}l_2 l_{c2}\dot{\varphi}\cos\varphi - \sigma h x\dot{x}l_2\dot{\varphi}\cos\varphi = -(m_2 l_{c2} + \sigma x h) g l_2\cos\varphi - (m_2 l_{c2} + \sigma x h) g l_2\cos\varphi + M. \qquad (5)$$

The system (1) solution allows getting the differential equations (4) and (5) that describe the dozer's movement on a straight line track, and determining control actions through the parameters of the machine in areas S_i of the digging operating cycle as the coefficients a_i in the dependence $V_{ot} = a_i\ V_p$. Such a dependence is typical for dozers with a single-motor drive with a hard pump hydraulic drive connection to the motor shaft.

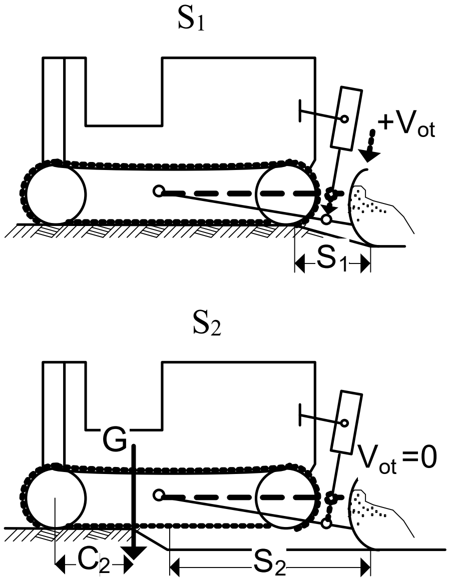


Figure 1. The movement of the tractor frame the beginning of digging

At the beginning of digging (Fig. 1), the frame of the tractor makes a strictly forward movement over a distance of S_1+S_2 without hesitation relatively its mass center. The blade cutting edge in the area S_1 dives into the soil to a depth equal to a predetermined cutting thickness *h*. Thus, the control action a_1 may be determined by the formula:

$$a_1 = \frac{30 i_{tr} m\, l_2}{\pi r_k F_z i_{pr} C_5 n}; \qquad (6)$$

where i_{tr}, i_{pr} - tractor transmission and hydraulic pump ratios; n - number of hydraulic cylinders; m - fluid mass in the hydraulic cylinders;

In the area S_2 the movement is made with a_2=0 until the mass center of the tractor won't move to the buttonhole edge.

On further movement the dozer "dives" in the drawn buttonhole (Fig. 2), so in the area S_3 it is necessary to lift the blade at a rate of V_{ot}, determined by the coefficient a_3:

$$a_3 = \mathrm{tg}\,\beta\left[e^{\frac{aV_{\Pi}t}{C_1+V_{\Pi}t}}\left(1+\frac{aC_1}{C_1+V_{\Pi}t}\right)-1\right]. \qquad (7)$$

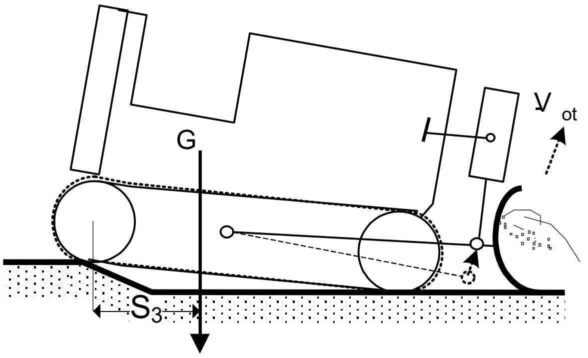


Figure 2 The movement the dozer "dives" in the drawn buttonhole

The area S_3 ends after the dozer's back gear hits the edge of the face and reverse alignment of tractor frame starts. Length of the alignment area is $S_4 \approx S_1$. Obviously, during this period it is necessary to start dropping the blade. The a_4 determines the rate of dropping the blade in the given area:

$$a_4 = \frac{C_3 S_1}{(C_4+S_3+V_{\Pi}t)^2}. \qquad (8)$$

To implement control actions $a_i = f(S_i, t, h)$ the dozer must be equipped with a vertical blade control system.

The developed models for bulldozer workflow elements are to be used for separate bulldozer units study with the help of analytical dependences between workflow parameters as well as for bulldozer general workflow simulation [8].

Elements models of bulldozer workflows being developed are intended both for the research of individual bulldozer units using analytical relationships between the parameters of the workflows and simulation of bulldozer workflows in general [9-10].

When constructing a discrete simulation model, the following assumptions are taken:
- the linear motion of the machine is investigated;
- the design is considered to be rigid;
- backlash and friction between the elements of the working equipment are not considered;
- the elastic- damping properties of movers are not considered;
- the dynamic characteristics of a diesel engine with fuel regulator and hydro mechanical transmission torque converter are replaced with static;
- coordinates of the treated soil surface are completely determined by the coordinates of the cutting edge of working organ;
- engine power selection to the drive of the working organ and auxiliaries are neglected;
- rate of motion of hydraulic cylinders rods for lifting and burial of the working organ is identical and does not depend on the applied load;
- mover rolling resistance is constant.

A simulation model is implemented in MATLAB / Simulink [7, 10, 13].

3 System configuration for the purpose of automation for bulldozer's workflow

The purpose of the experimental studies was to compare the performance of a bulldozer equipped with modernized and serial working equipment. The main goal of the experiment is to collect the data needed to identify the bulldozer's workflow [8-12].

The sensors connection scheme is shown in Figure 3. As a result of measurements, signals $P(t)$, $v(t)$ and digging depth $l(t)$ were obtained, used to identify the working process of the bulldozer.

To collect experimental information on the parameters of the working process of the bulldozer in dynamics, laboratory studies of the process of cutting the soil with a flat knife during movement were carried out. The automated collection of the values, of the speed v and the resistance force movement P was carried out. Experimental signals are used to identify the workflow using neural network mathematical models.

Experimental data loaded simulation model. Simulation tasks:

- To single out the main sub-systems in bulldozer's structure and interrelations between the sub-systems;
- To develop analytic and simulation models for workflow elements and to include them into the general structure of the model.

The structure meets the goals of workflow control. When moving soil by the bulldozer, it is necessary to utilize bulldozer's traction capacity in full keeping the nominal traction value; when surfacing, the altitudes of the right and left side of the blade are to correspond the design marks. The key element at the scheme (Figure 4) shows the choice for the first or the second operational mode.

At developing the models, we use mathematical apparatus of the random processes theory, transfer functions, table interpolation, numerical solution of algebraic equations and ordinary differential equations in the Cauchy form. Random changes in the coordinates of untreated soil surface, as well as normalized fluctuations in the resistance forces on the working organ, caused by the heterogeneity of the soil are highlighted among the disturbing effects on the working organ of the bulldozer from soil conditions. Loading conditions on the working organ are due to random variation in the dig depth and heterogeneity of soil properties.

Soil digging process with bulldozer working organ is studied on the base of the finite element model of the soil mass, a mathematical model of random forces of resistance on the working organ being developed. The actual bulldozer velocity depends on the strength and the properties of the mover, transmission and the power unit. In its turn, disturbance parameters, movement of the working organ and the formation of stress depend on the velocity. Bulldozer drive model and mover interaction with the soil include engine model, mechanical and hydro mechanical transmission, as well as slipping. Control system regulator depending on the objectives, control algorithm and the incoming data from the bulldozer as a control object produces electrical signals to the electro-hydraulic distributors being part of the working organ hydro drive. Lifting or burying the blade is done to control either the pulling power, or the blade coordinates.

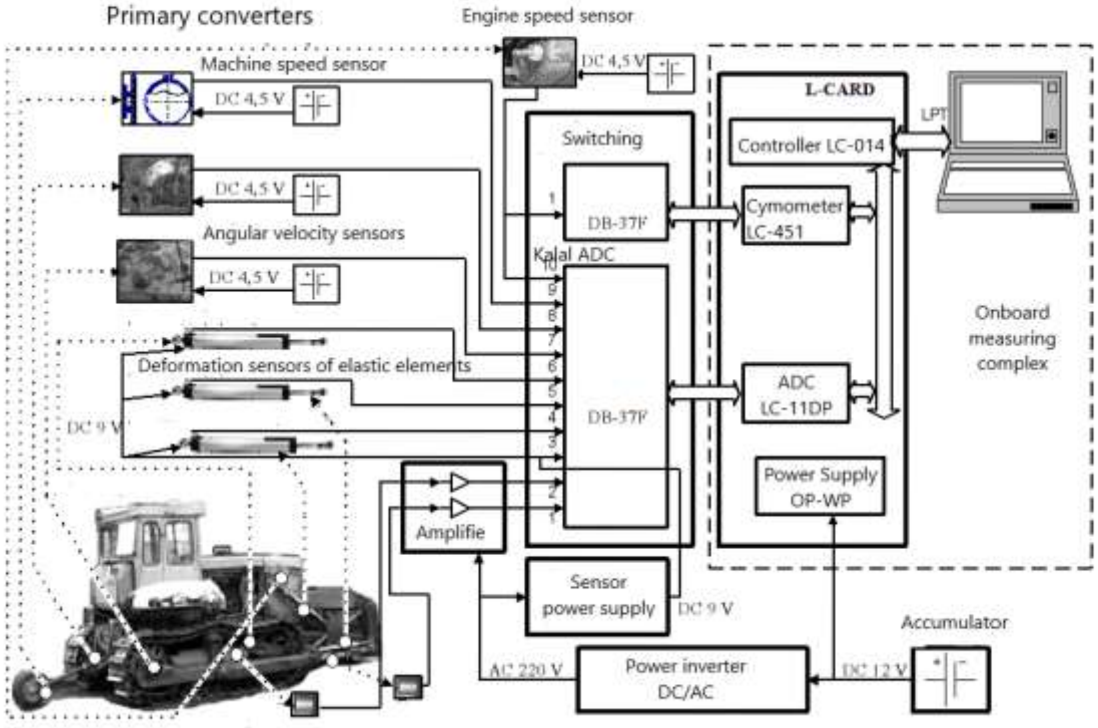


Figure 3. Connection scheme of sensors

After training the model, load the data into the on-board complex of the bulldozer to check the adequacy of the model. To evaluate the proposed system, two experiments were carried out:

- Operator controlled without using an automatic system (Fig. 4a);
- When controlling the operator using the developed system (Fig. 4b);

After that, the results were compared.

Thus, it can be noted that the system allows you to simulate a bulldozer digging surface with a deviation not exceeding 2 cm.

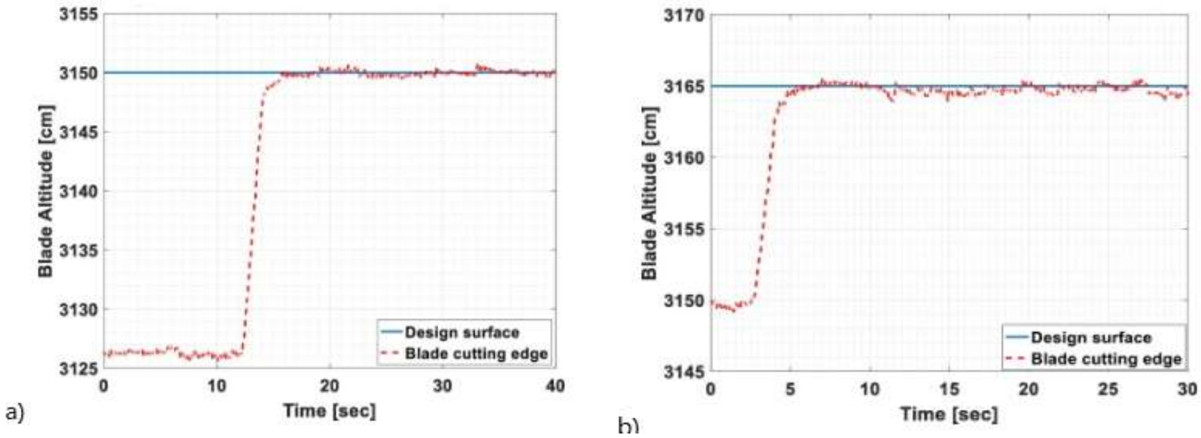
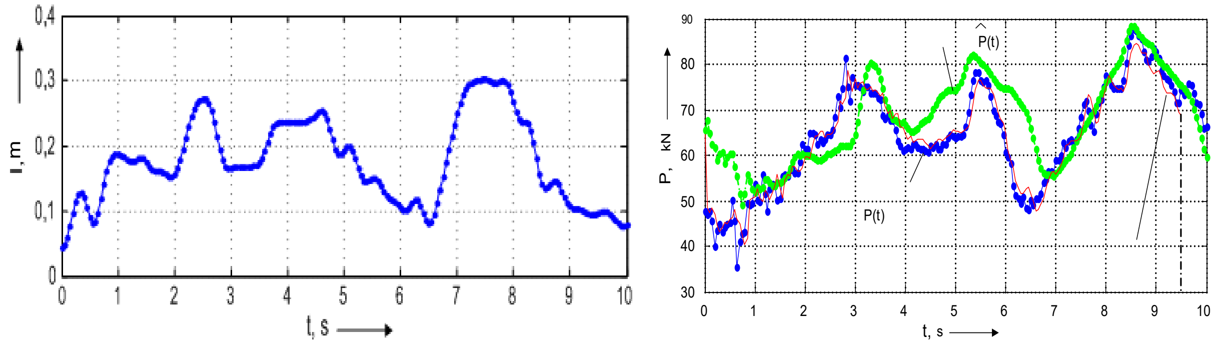


Figure 4. Verification system modeling surface

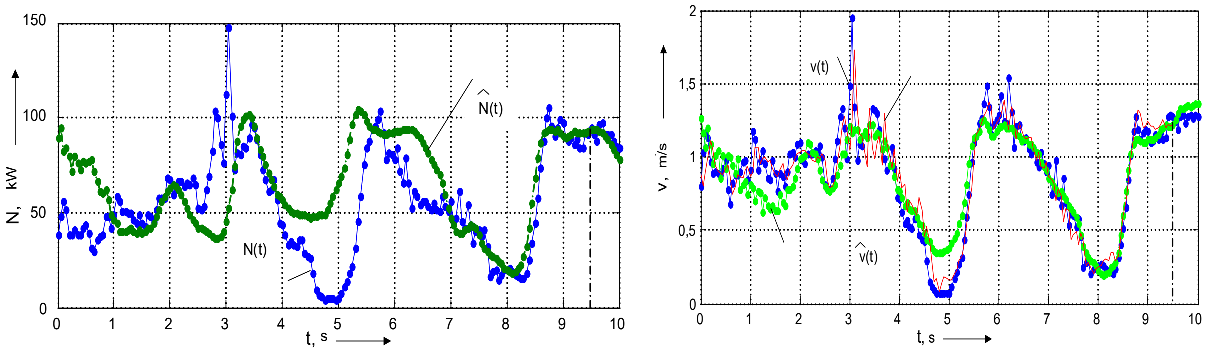
4 Conclusions and Results

Input model signal, used for training, simulation and verification is presented in Fig. 5a. Adaptive learning for the model is stopped at time t=9,5 sec. Receiving at this moment a neural network model parameter values, modeled digging resistance force and speed of the machine (Fig. 5b, 5d) are accomplished, as well as the forecast for another 0.5 seconds is developed [10].



a) Deepening dozer Blade

b) Digging Resistance Force



c) Bulldozer pulling power

d) Bulldozer current velocity

Figure 5. Comparison of Bulldozer operational parameters obtained with the Model and actual operational parameters

Figure 5c shows the output of neural network models-pulling power of the bulldozer. In modeling and prediction of the neural network output is close to the experimental data only in the time interval of 7-10 sec. This is due to a change in unmeasurable chip thickness, as well as the rapidly changing conditions of the mover clutch with the ground. Therefore, the parameters of the adaptive neural network model must be adjusted in real time. The accuracy of prediction of pulling power N(t) has been estimated; the average relative error being 14.7 % on an interval from 7 to 10 s [7]. Identification Technique of bulldozer workflows and models obtained on its basis, are designed for use in the development of adaptive systems of automatic workflow management of bulldozer [11-14].

Identification technique of the dozer's working processes and models obtained on its base, are intended to be used in the development of adaptive systems of automatic control of the dozer's working process.

For the formation of the control actions influencing the bulldozer, particularly electrical signals actuating control valves of hydraulic cylinders lifting and lowering the working organ, the structure and algorithms of adaptive neural network controller have been designed.

References

[1] Roberts G., Dodson A. and Ashkenazi V. Global Positioning System aided autonomous construction plant control and guidance Atom. Constr., 8 (5) (1999), pp. 589-595, 10.1016/S0926-5805(99)00008-4.

[2] Trimble Corporation. Civil Engineering and Construction, Grade Control for Dozers. On-line https://construction.trimble.com/products-and-solutions/grade-control-dozers, Accessed 4th Jul 2019.

[3] Komatsu Corporation. Intelligent Machine Control. On-line https://www.komatsu.eu/en/Komatsu-Intelligent-Machine-Control, Accessed 4th Jul 2019.

[4] Roberts G., Ogundipe O. and Dodson A. Construction plant control using RTK GPS Proceedings of the XXII International Congress of the FIG, 6 (2002), pp. 1-13 https://www.fig.net/resources/proceedings/fig_proceedings/fig_2002/TS6-2/TS6_2_roberts_ogundipe_dodson.pdf

[5] Jehle P., Bulgakov A. and Tokmakov G. Mechatronics Systems and Logistic Service for Ensuring the Smooth Construction Process. // Creative Construction Conference 2014 June 21–24, 2014 Prague, Czech Republic. – Budapest, Szent István University, Proceedings CC2014, pp. 242-247.

[6] Bulgakov, A. and Tokmakov, G. ERP-systems, logistics and mechatronics systems for ensuring the smooth construction process // Journal of Applied Engineering Science Volume 16, Issue 1, 2018, Pages 1-4. ISSN: 14514117 DOI: 10.5937/jaes16-14653

[7] Bulgakov, A., Tokmakov, G., Otto, J. and Langosch, K. Evaluation of the construction project success with use of neural networks // Proceedings of the Creative Construction Conference (2018), 30 June - 3 July 2018, Ljubljana, Slovenia, pp. 46-50. ISBN 978-615-5270-45-1 DOI: 10.3311/CCC2018-007 http://2018.creative-construction-conference.com /wp-content/uploads/CCC2018_Proceedings.pdf

[8] Krapivin D., Nefedov V. and, Tokmakov G. Mathematical model for the movement of mechatronischen devices for the intelligent building site, Mechatronik, Lik, Nowotscherkassk, 2010.- S. 50-54.

[9] Shestopalov K. Hoisting-and-transport, building and road machines and equipment. Moscow: Academy, 2009. P. 67-72.

[10] Bulgakov A., Bock, T. and Tokmakov G. Adaptive control of bulldozer's workflows // 5th International Construction Specialty Conference, Vancouver, June 7 - 10, 2015, pp. 434-442.

[11] ROBO Industries Autonomous Machine Control System On-line http://www.aee.us.com/page-video.html, Accessed 4th Jul 2019

[12] Guangqiu Yin, He Fuyin, Zhanfu Li, Jingxiu Ling Workspace description and simulation of a backhoe device for hydraulic excavators, 103325 Automation in Construction Volume 119, November 2020.

[13] Yong-Seok Lee, Sang-Ho-Kim, Jongwon Seo, Jeakweon Han and Chang-Soo Han. Blade control in Cartesian space for leveling work by bulldozer, Automation in Construction Volume 118, October 2020/

[14] Rutkovskij L. and Pilinskij M. Neural networks, genetic algorithms and fuzzy systems., Gorzachaza Liniza TELEKOM, 2004.