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Научная статья

ПРИМЕНЕНИЕ МЕТОДА «ЧИСТОЕ ПРЕСЛЕДОВАНИЕ» (PURE PURSUIT) ДЛЯ УПРАВЛЕНИЯ БЕСПИЛОТНЫМ АВТОГРЕЙДЕРОМ

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АННОТАЦИЯ

Введение. *Актуальная задача создания перспективных систем беспилотного управления дорожно-строительных машин может быть решена путем проведения теоретических исследований на математических моделях.*
Материалы и методы. *Одна из важных проблем при создании системы управления движением беспилотной машины – это составление алгоритма следования заданной траектории. Наиболее известным методом следования траектории является метод «чистое преследование», успешно применяемый для управления движением мобильных роботов.*
В связи с этим была сформулирована цель исследования – адаптировать метод «чистое преследование» для управления беспилотным автогрейдером. Для достижения поставленной в работе цели были решены следующие задачи: разработана математическая модель движения автогрейдера с передними управляемыми колесами, разработана математическая модель системы управления движением автогрейдера, предложен интегральный критерий для оценки эффективности работы системы управления движением беспилотного автогрейдера, проведены теоретические исследования математической модели и получены зависимости интегрального критерия от конструктивных и эксплуатационных параметров автогрейдера и от параметра метода управления (дальность видимости), найдены оптимальные значения дальности видимости при различных значениях длины базы, коэффициента базы и скорости машины по предложенному критерию эффективности.
Результаты. *В результате аппроксимации полученных оптимальных значений метод «чистое преследование» был модифицирован для управления беспилотным автогрейдером с учетом его конструктивных особенностей и скорости передвижения.*
Полученные результаты могут быть использованы при создании опытных образцов систем беспилотного управления дорожно-строительных машин.

КЛЮЧЕВЫЕ СЛОВА: *автогрейдер, беспилотный, траектория, машина, управление, алгоритм, метод управления, курс, чистое преследование.*

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Original article

PURE PURSUIT METHOD USE TO CONTROL UNMANNED MOTOR GRADER

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ABSTRACT

Introduction. *A relevant objective of implementing the advanced systems of self-driving road construction vehicles can be accomplished by mathematical modelling. One of the important issues when creating a motion control system for a self-driving vehicle is to develop a trajectory following algorithm. The most well-known method of following the trajectory is a pure pursuit method, which is successfully used to control the movement of mobile robots.*
Materials and methods. *Hence, the research objective has been defined and is to adapt the pure pursuit method to control an autonomous grader. To achieve the research objective, the task of a mathematical model of the motor grader movement with front steering wheels has been developed, and a mathematical model of the motor grader motion control system has been compiled. Besides, we propose an integral criterion to evaluate the efficiency of the motion control system of a unmanned grader. Some theoretical studies of the mathematical model have been carried out and the dependencies of the integral criterion on the design and operational parameters of the grader, as well as on the parameter of the control method (visibility range) have been obtained. Moreover, the optimal values of the visibility range for various values of the base length, base coefficient and machine speed have been defined according to the proposed efficiency criterion.*
Results. *As a result of approximating the obtained optimal values, the pure pursuit method has been modified to control a self-driving motor grader, taking into account its design features and travel speed.*
The results obtained can be used to create the prototypes of unmanned control systems for road construction vehicles.

KEYWORDS: *motor grader, unmanned vehicle, trajectory, vehicle, control, algorithm, control method, course, pure pursuit.*

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INTRODUCTION

Nowadays, unmanned technologies are widely used in various branches of industry and economy. The adoption of self-driving technologies in the construction industry, namely in heavy equipment, is a promising direction that will develop quite rapidly in the next few years [1]. A motor grader is a construction machine similar in control algorithm to a self-driving vehicle. One of the well-known methods of controlling the self-driving cars is the «pure pursuit» method[1, 2]. This method is used to control mobile robots[3] [2,3,4], unmanned vehicles[4, 5] [5], agricultural machines [6], logging harvesters [7], underwater uninhabited vehicles [8], etc. However, there are no studies of this method when driving a grader.

Driving an unmanned grader differs from driving an unmanned vehicle mainly by purpose [9,10,11]. The main purpose of the grader movement is the movement of the working body in accordance with the project of the earthen structure. The trajectories of the basic machine and its parts are secondary in this case. In this case, the trajectory is an alternation of sections of rectilinear motion during the working stroke and reversals[6] [10,12].

The setting parameter of the «pure pursuit» method is the look-ahead distance. With an increase in this parameter, the machine tends to follow the trajectory more precisely and, thereby, the yaw along the trajectory increases. With a decrease in this parameter, the movements of the machine become smoother, but with sharp turns of the trajectory, the machine begins to “cut the corners”.

Several works were devoted to finding the optimal value of the look-ahead distance for the car7 [5]. Some authors even suggested using a dynamic look-ahead distance, i.e. a change depending on the speed and accuracy of the trajectory[7].

PROBLEM STATEMENT

The purpose of this work is to adapt the «pure pursuit» method to control an unmanned grader. To achieve this goal, it is necessary to solve a number of tasks: to make mathematical models of the movement of a grader with front steerable wheels and a motion control system, to justify a criterion for evaluating the effectiveness of the motion control system of an unmanned grader, to conduct theoretical studies of the mathematical model and to obtain the dependences of the efficiency criterion on the design and operational parameters of the grader and on the parameter of the control method (visibility range), to find optimal values of the visibility range at different values of the base length, the coefficient of the base and the speed of the machine according to the proposed efficiency criterion and on the basis of the data obtained to propose a modified method of «pure pursuit».

MATHEMATICAL MODEL

The mathematical model of movement was developed on the basis of a two-dimensional grid of turning a motor grader with front steering wheels in the Earth coordinate system $O_{EARTH}X_{EARTH}Y_{EARTH}$ (figure 1).

When turning a motor grader with front steering wheels, the elementary displacement of the midpoint of the rear axle O_R can be calculated by the following formula[8] [13,14]:

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[1] Omead Amidi. Integrated Mobile Robot Control. Technical Report CMU-RI-TR-90-17, Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, May 1990.

[2] R. Craig Coulter. Implementation of the «pure pursuit» Path Tracking Algorithm. Technical Report CMU-RI-TR-92-01, Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, January 1992.

[3] Alessandro De Luca, Giuseppe Oriolo. Feedback Control of a Nonholonomic Car-like Robot. 2004.

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[5] Matthew J. Barton. Controller Development and Implementation for Path Planning and Following in an Autonomous Urban Vehicle. Undergraduate thesis, University of Sydney, November 2001.

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[8] Portnova A. A. the Problem of minimizing the turning radius grader with articulated / Innovation, quality and service in engineering and technology. Kursk: Closed Joint Stock Company "University Book", 2014. pp. 97-99.

$$dS = R_R d\gamma, \tag{1}$$

whence it follows that:

$$Vdt = R_R d\gamma; \tag{2}$$

$$\frac{d\gamma}{dt} = \frac{V}{R_R}, \tag{3}$$

where S is the midpoint movement of the rear axle, R_R is the turning radius of the rear axle midpoint, γ is the heading angle of the motor grader, V is the velocity of the motor grader.

The turning radii of the grader can be defined by the following formula8 [13, 14]

$$R_R = \frac{L}{tg\alpha_W}; \tag{4}$$

$$R_F = \frac{L}{\sin\alpha_W}, \tag{5}$$

where R_F is the turning radius of the front axle midpoint, L is the length of the grader base, α_W is the steering angle of the front wheels.

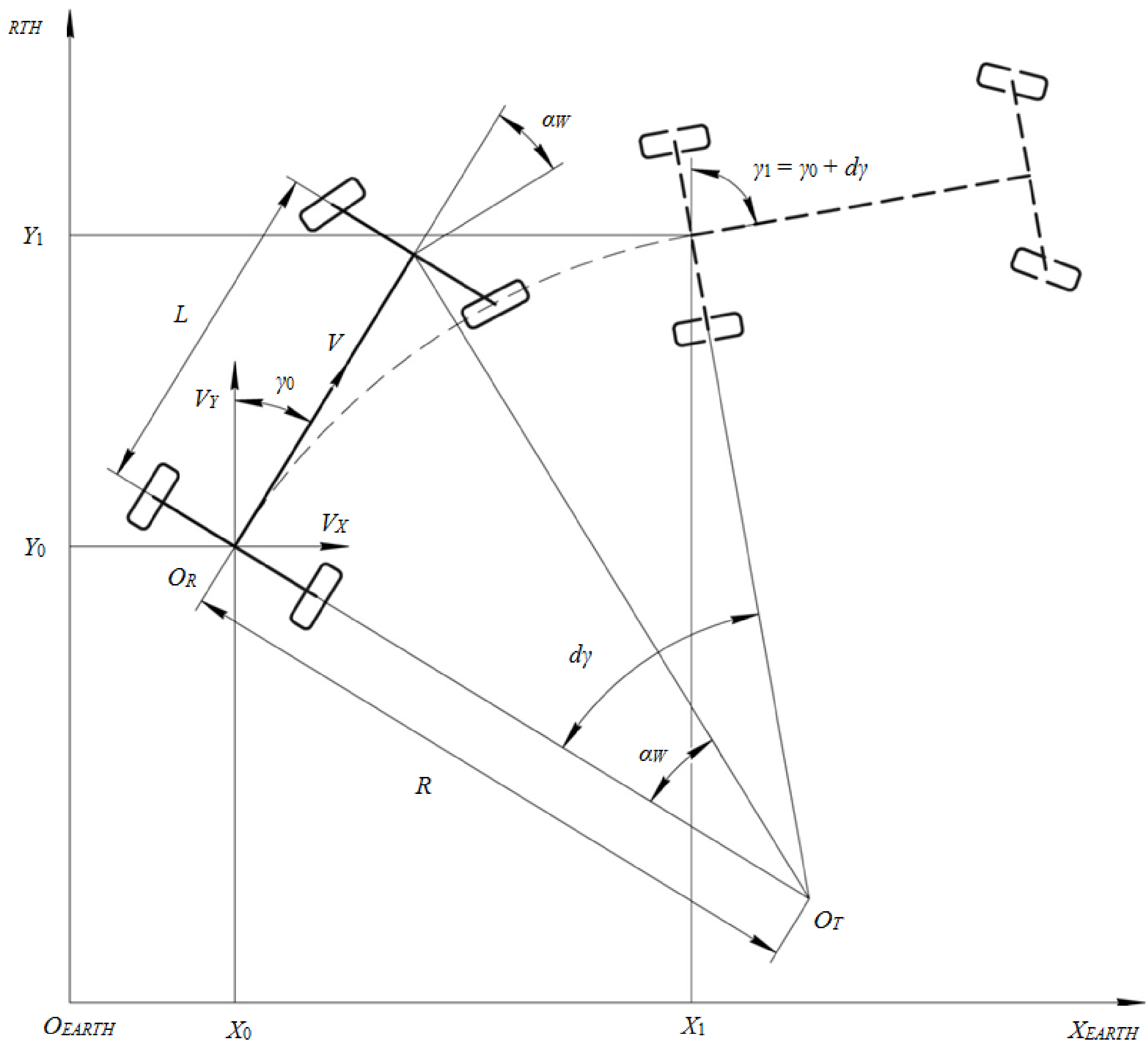

Figure 1 – Two-dimensional grid of turning the motor grader with front steering wheels [14]

Substituting formula (4) into formula (3) the following equation is obtained:

$$\frac{d\gamma}{\mathrm{dt}} = \frac{V}{L}\mathrm{tg}\alpha_W. \quad (6)$$

The velocity vector of the rear axle midpoint can be decomposed into the velocity projections along the axis X_{EARTH}:

$$V_X = V\sin\gamma, \quad (7)$$

or:

$$\frac{\mathrm{dx}}{\mathrm{dt}} = V\sin\gamma; \quad (8)$$

and along the axis Y_{EARTH}:

$$V_Y = V\cos\gamma, \quad (9)$$

or

$$\frac{\mathrm{dy}}{\mathrm{dt}} = V\cos\gamma. \quad (10)$$

The set of formulas (4), (8) and (10) can be represented in the form of a mathematical model (figure 2) compiled in the MATLAB Simulink software.

PURE PURSUIT METHOD DESCRIPTION

The «pure pursuit» method consists of a geometric calculation of the radius of the circular arc connecting the location of the rear axle with the target point on a trajectory in front of the vehicle. The target point is determined based on the look-ahead distance L_0 from the midpoint of the rear axis to the trajectory[1,2,3,4,5,7] [2-8].

The turning angle of the motor grader can be defined using only the location of the target point and angle φ between the machine course vector and the prediction vector. Using the data of figure 3, we can record the following formulas [1,2,3,4,5,7] [2-9].

$$\frac{L_0}{\sin 2\phi} = \frac{R}{\sin(90° - \phi)}, \quad (11)$$

$$R = \frac{L_0}{2\sin\phi} = \frac{L_0^2}{2\Delta Y_1}, \quad (12)$$

where L_0 is the look-ahead distance, ΔY_1 is the deviation of the midpoint of the rear axle from the trajectory, φ is the angle between the longitudinal axis of the motor grader and the direction to the target point.

The required turning angle of the motor grader can be calculated using the appropriate equations for a specific type of a machine. For example, for a grader with front steering wheels, a turning angle is defined by the following formula[1,2,3,4,5,7] [2-9]:

$$\frac{L_0^2}{2\Delta Y_1} = \frac{L}{\mathrm{tg}\alpha_W}. \quad (13)$$

Accordingly, the wheel turning angle is defined by the formula:

$$\alpha_W = \arctan\left(\frac{2\Delta Y_1 L}{L_0^2}\right). \quad (14)$$

Thus, the «pure pursuit» method is a proportional regulator of the grader transverse displacement error.

EFFICIENCY CRITERION

The main purpose of the grader movement is to move the blade in accordance with the earth structure project. Consequently, the deviation of the midpoint of the blade (B) from the specified trajectory should be used as a performance criterion of the selected control method [9,15].

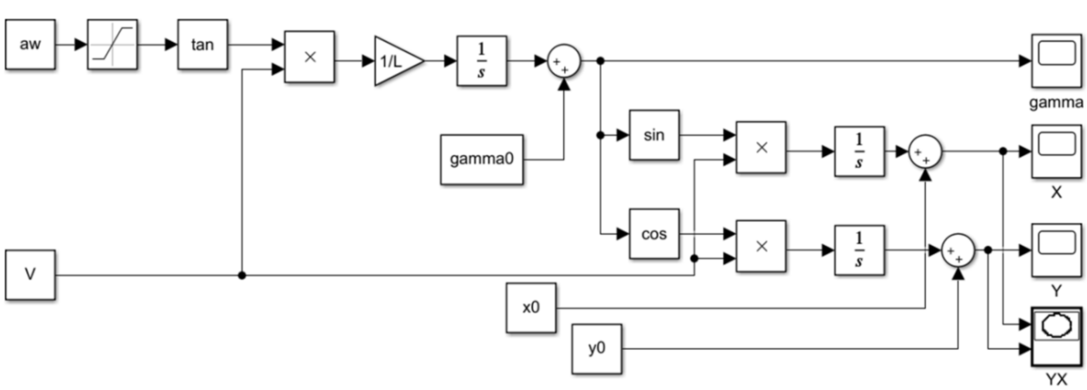

Figure 2 – Mathematical model of turning a motor grader with front steering wheels [14]

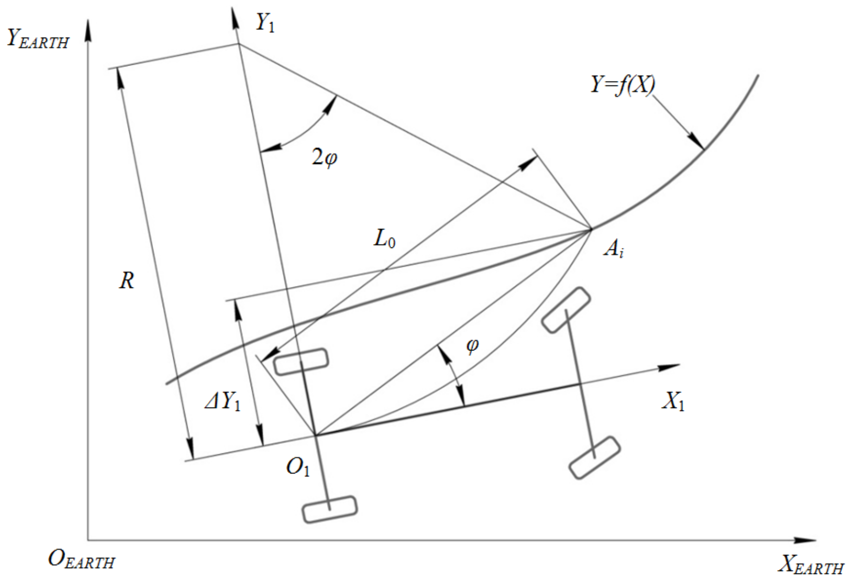

Figure 3 – Design diagram of the «pure pursuit» algorithm[1,2,3,4,5,7] [2-9]

The given parameter can be quantified using the integral indicator, i.e. the area between the specified trajectory and the trajectory of the blade midpoint and is calculated by the formula [9,15,16]

$$E_T = \int_0^{\infty} |\Delta y(x)| \mathrm{d}x, \quad (15)$$

whereis $y(\infty) - y(x)$ is the trajectory deviation of the blade midpoint from the value (∞) that corresponds to the specified trajectory [9,15,16].

The criterion E_T geometrically represents the shaded area in figure 4a. The transient process shown in figure 4a is caused by a disturbance, for example, a stepwise change of the given trajectory. The smaller the shaded area, the more preferable the transition process [9,15,16].

This integral criterion can be used not only to assess the control quality, but also to optimize the variable parameters for the control system synthesis. Moreover, the absolute value of the criterion E_T is not significant. Using the equations for E_T and system transfer functions, the dependences of the criterion E_T on the variable parameters of the control system and their optimal values can be obtained [9,15,16].

When using the module, the integral criterion E_T can be applied to the systems which transients have oscillation and change the sign (figure 4b) [9,15,16].

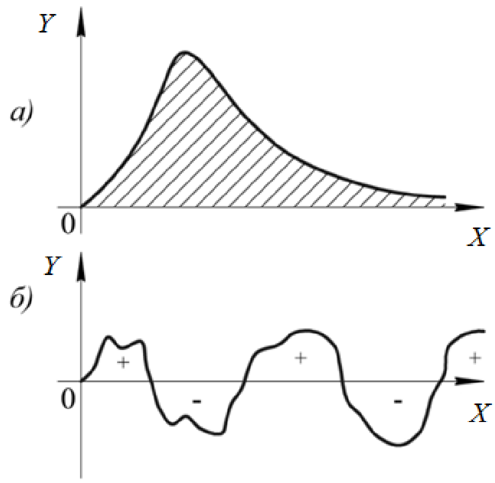

Figure 4 – Integral quality criteria [9,15]

More complex integral criteria based on the second and following derivatives of ΔY can be used. Their application will bring the transients closer to the second and higher order curves [9,15,16].

RESEARCH RESULTS

During theoretical investigation of the mathematical model, a step change of the trajectory by 1 m was used as an input signal.

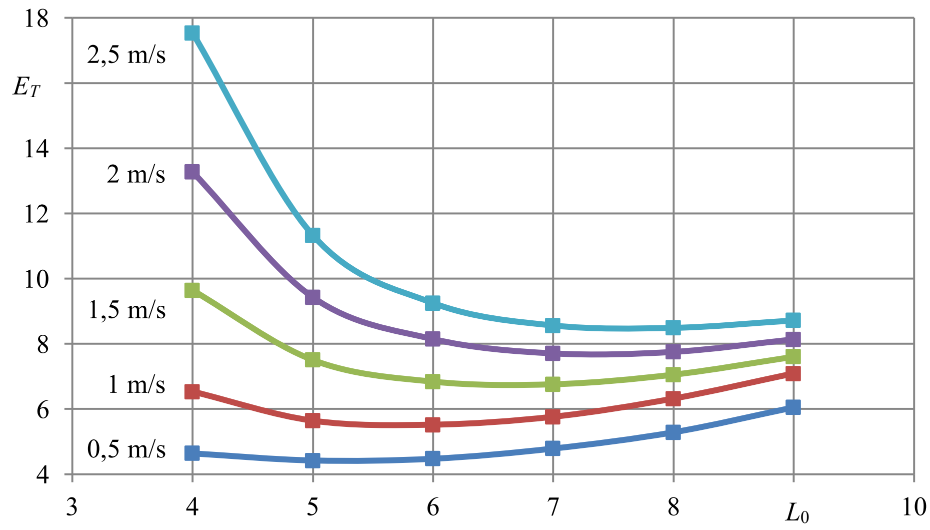

Figure 5 – The influence of the look-ahead distance L_0 on the integral criterion E_T at different velocities of the motor grader V
Source: compiled by the author

The studies have shown that the following parameters of the mathematical model, namely the look-ahead distance L_0, the length of the motor grader base, the coefficient of the motor grader base, the motor grader velocity have the strongest influence on the integral criterion E_T (figures 5, 6, 7).

The coefficient of the motor grader base determines the position of the blade in the base and is defined by the following formula:

$$K_b = \frac{L_1}{L}, \tag{16}$$

where L_1 is the distance from the front axle to the blade.

The main objective of theoretical studies of the mathematical model of the motor grader in a dynamic mode was to determine the optimal numerical values of the control method parameters, their dependences on the design and operational parameters of the grader.

The model parameters were divided into three groups: fixed parameters, stochastic parameters, variable parameters [17,18].

The variable parameters have been divided, in turn, into three subgroups:

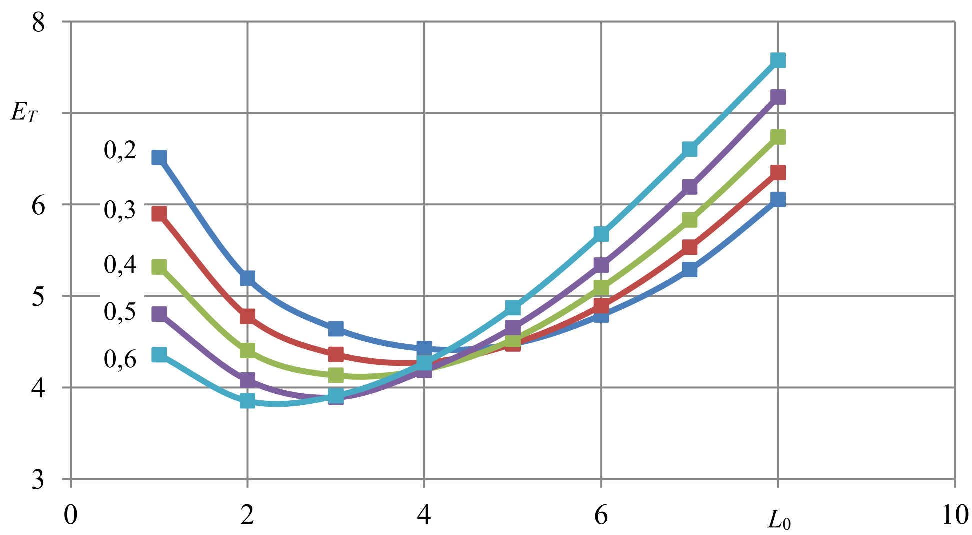

Figure 6 – The influence of the look-ahead distance L_0 on the integral criterion E_T at different values of the base coefficient K_b.
Source: compiled by the author.

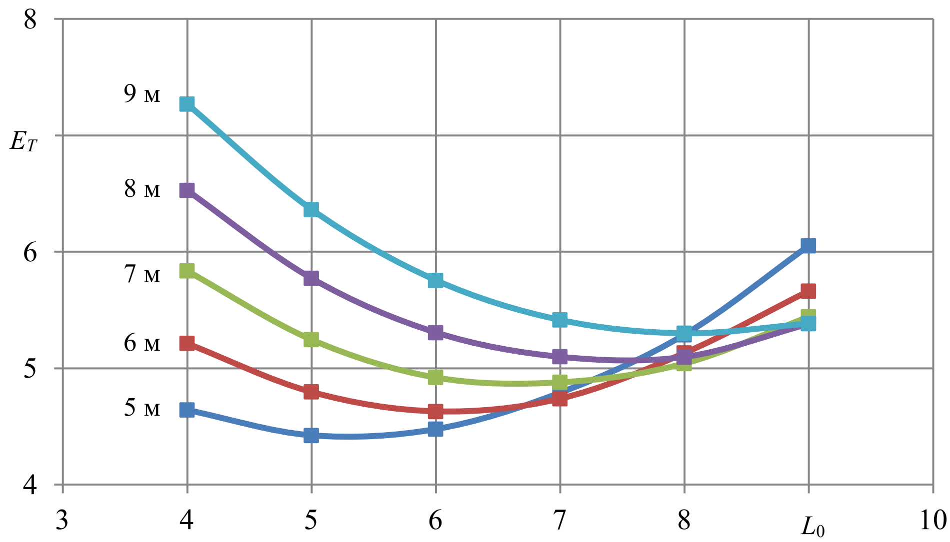

Figure 7 – The influence of the look-ahead distance L_0 on the integral criterion E_T at different values of the base length L
Source: compiled by the author.

Design parameters of the motor grader (base length, base coefficient).

Operational parameters of the motor grader (vehicle velocity).

Parameters of the control method (look-ahead distance L_0).

The obtained dependences have been presented in the form of a graphical complex of the surfaces for different base lengths and different values of the motor grader velocity (figures 8, 9, 10, 11, 12).

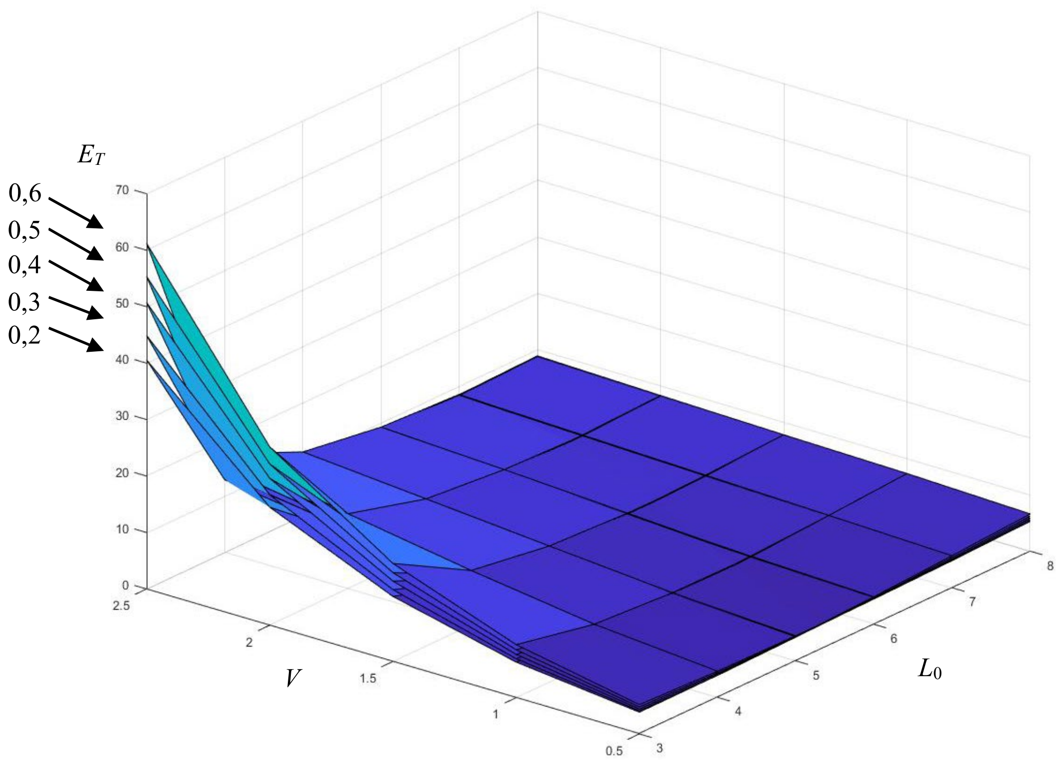

Figure 8 – Dependences of the integral criterion E_T on the look-ahead distance L_0 and velocity V at different values of the base coefficient (L=5 m)
Source: compiled by the author.

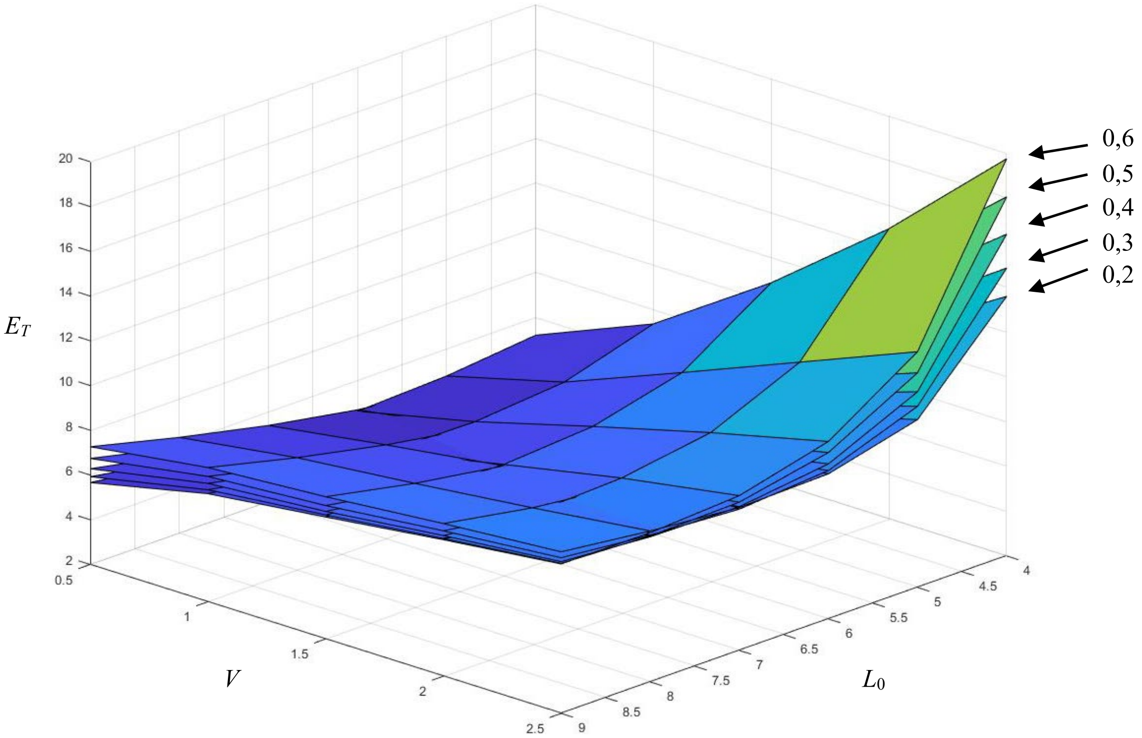

Figure 9 – Dependences of the integral criterion E_T on the look-ahead distance L_0 and velocity V at different values of the base coefficient (L=6 m)
Source: compiled by the author.

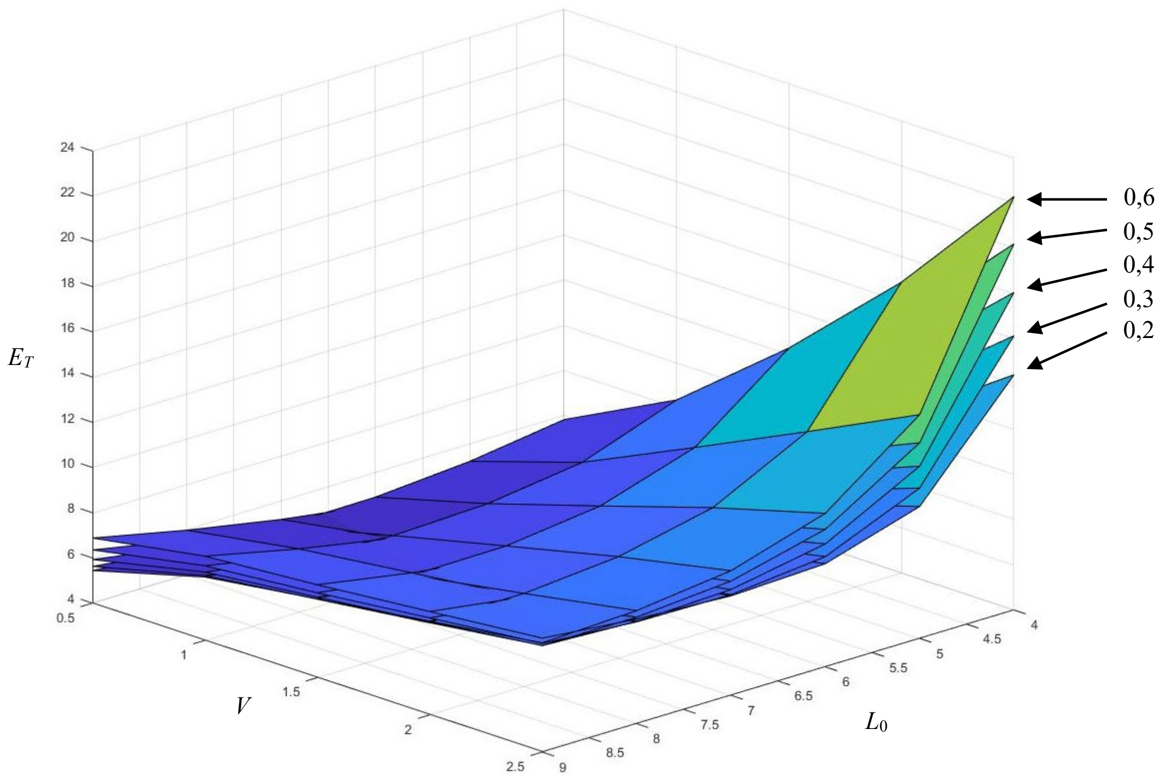

Figure 10 – Dependences of the integral criterion E_T on the look-ahead distance L_0 and velocity V at different values of the base coefficient (L=7 m)
Source: compiled by the author.

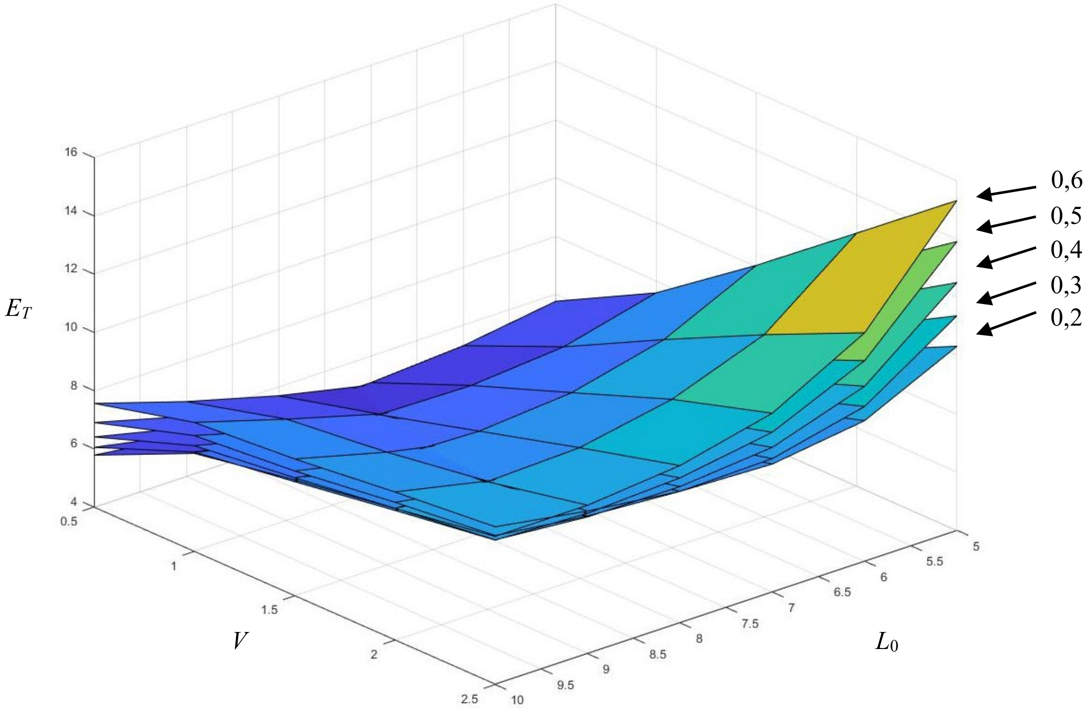

Figure 11 – Dependences of the integral criterion ET on the look-ahead distance L0 and velocity V at different values of the base coefficient (L=8 m)
Source: compiled by the author.

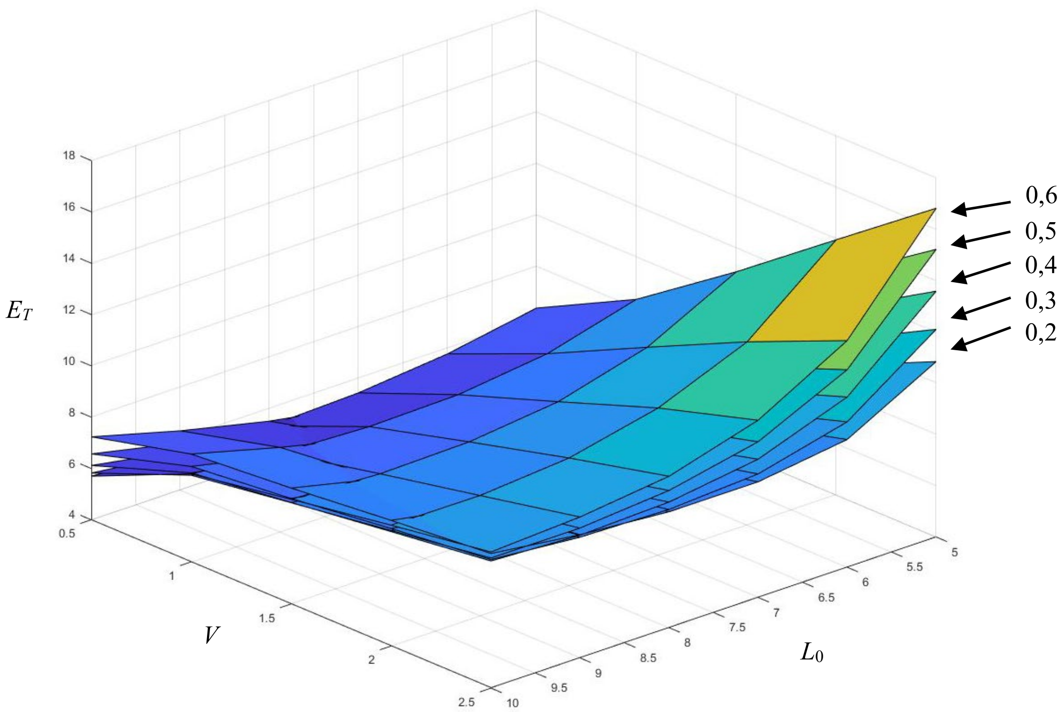

Figure 12 – Dependences of the integral quality criterion on the look-ahead distance L_0 and velocity V at different values of the base coefficient (L=9 m)
Source: compiled by the author.

Based on the obtained dependences, we can conclude that the grader speed significantly affects the efficiency criterion. Since speed is not taken into account in the original method of «pure pursuit», we propose to modify the method and introduce speed into it.

The obtained dependences have been approximated with the 4th degree polynomials with determination coefficients R^2 of at least 0,99

$$E_T = a_4 \cdot L_0^4 + a_3 \cdot L_0^3 + a_2 \cdot L_0^2 + a_1 \cdot L_0 + a_0. \tag{17}$$

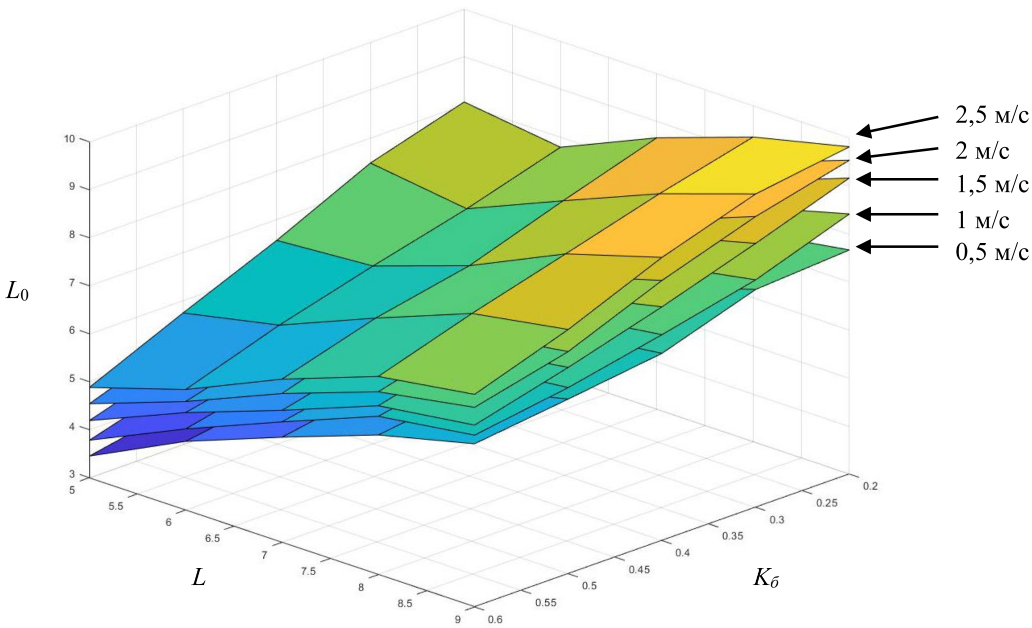

Figure 13 – Dependences of the optimal values of the look-ahead distance L_0 at different values of speed, base length and base coefficient
Source: compiled by the author.

Due to the optimization carried out by the Newton method, for the minimality condition of the integral criterion, the optimal values of the look-ahead distance L_0 have been obtained for various values of the base length, base coefficient and speed. Figure 13 shows the graphs of the obtained optimal values of the look-ahead distance.

The obtained dependences of the optimal values of the look-ahead distance on the speed, base length and base coefficient have been approximated with regression equations and are presented in table 1.

The regression equations have the form of $L_0 = a_0 \cdot V + a_1$. From the regression equations, it will be obvious that the multiplier a_0 depends only on the base length L and can be approximated with the following equation

$$a_0 = 1{,}6 + 0{,}04 \cdot L. \tag{18}$$

Table 1
The regression equations of the look-ahead distance L_0
Source: compiled by the author.

L	K_b	The regression equation	R^2
5	0,2	$L_0 = 1{,}4 \cdot V + 4{,}338$	0,967
	0,3	$L_0 = 1{,}4 \cdot V + 4{,}07$	0,999
	0,4	$L_0 = 1{,}4 \cdot V + 3{,}666$	0,974
	0,5	$L_0 = 1{,}4 \cdot V + 3{,}282$	0,985
	0,6	$L_0 = 1{,}4 \cdot V + 2{,}976$	0,984
6	0,2	$L_0 = 1{,}36 \cdot V + 5{,}102$	0,968
	0,3	$L_0 = 1{,}36 \cdot V + 4{,}616$	0,961
	0,4	$L_0 = 1{,}36 \cdot V + 4{,}146$	0,976
	0,5	$L_0 = 1{,}36 \cdot V + 3{,}742$	0,972
	0,6	$L_0 = 1{,}36 \cdot V + 3{,}332$	0,971
7	0,2	$L_0 = 1{,}32 \cdot V + 5{,}774$	0,956
	0,3	$L_0 = 1{,}32 \cdot V + 5{,}282$	0,991
	0,4	$L_0 = 1{,}32 \cdot V + 4{,}688$	0,986
	0,5	$L_0 = 1{,}32 \cdot V + 4{,}176$	0,983
	0,6	$L_0 = 1{,}32 \cdot V + 3{,}676$	0,976
8	0,2	$L_0 = 1{,}28 \cdot V + 6{,}36$	0,872
	0,3	$L_0 = 1{,}28 \cdot V + 5{,}762$	0,958
	0,4	$L_0 = 1{,}28 \cdot V + 5{,}24$	0,975
	0,5	$L_0 = 1{,}28 \cdot V + 4{,}624$	0,975
	0,6	$L_0 = 1{,}28 \cdot V + 4{,}054$	0,981
9	0,2	$L_0 = 1{,}24 \cdot V + 6{,}876$	0,844
	0,3	$L_0 = 1{,}24 \cdot V + 6{,}362$	0,881
	0,4	$L_0 = 1{,}24 \cdot V + 5{,}708$	0,958
	0,5	$L_0 = 1{,}24 \cdot V + 5{,}084$	0,982
	0,6	$L_0 = 1{,}24 \cdot V + 4{,}41$	0,973

Table 2
The coefficients a_1 in the regression equations of the look-ahead distance L_0
Source: compiled by the author.

$K_б$ / L	0,2	0,3	0,4	0,5	0,6
0,5	4,388	4,07	3,666	3,282	2,976
1	5,102	4,616	4,146	3,742	3,332
1,5	5,774	5,282	4,688	4,176	3,676
2	6,36	5,762	5,24	4,624	4,054
2,5	6,876	6,362	5,708	5,084	4,41

The free coefficients a_1 in the regression equations depend on the base length and base coefficient. For further approximation, they were summarized in table 2 and the resulting dependence was approximated by the following equation

$$a_1 = 3{,}2 - 5 \cdot K_б + 0{,}5 \cdot L. \quad (19)$$

Therefore, a modified method of «pure pursuit» adapted to control the motor grader has been proposed. The dependence of the optimal value of the look-ahead distance on the speed, base length and base coefficient is represented by the following formula

$$L_0 = a_0 \cdot V + a_1. \quad (20)$$

where $a_0 = 1{,}6 + 0{,}04 \cdot L$,
$a_1 = 3{,}2 - 5 \cdot K_б + 0{,}5 \cdot L$, are applied for the motor grader with front steering wheels.

After substituting formula (20) into formula (14), we obtain a formula for calculating the front wheels turning angle adapted to the grader:

$$\alpha_K = \arctan\left(\frac{2\Delta Y_1 L}{(a_0 V + a_1)^2}\right). \quad (21)$$

DISCUSSION AND CONCLUSION

The developed mathematical models of the movement of a motor grader with front steerable wheels and a motor grader motion control system made it possible to conduct theoretical studies and identify the dependencies of the integral criterion on the design and operational parameters of the grader and on the parameter of the control method (look-ahead distance). After optimization, optimal values of the look-ahead distance were found for different values of the base length, base coefficient and machine speed according to the proposed efficiency criterion. As a result of the approximation of the obtained optimal values, the «pure pursuit» method was modified to control an unmanned grader, taking into account its design features and speed of movement. The results obtained can be used to create prototypes of unmanned control systems for road construction vehicles.

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