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FARM TRACTOR MECHATRONIC STEERING MODULE

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This paper proposes a mechatronic steering module consisting of two parts which allows you to increase the speed of the automatic control system, simplify the design and reduce its cost. In the electromechanical part of the mechatronic module a brushless DC motor is used, its rotor being an integral part of the steering wheel. To change the position of the rotor is to turn the steering wheel without intermediate mechanisms. To implement the software and hardware, a mathematical model was developed. On the basis of this model an algorithm was obtained that describes the movement pattern of a tractor with an agricultural machine. The mechatronic module was tested in comparison with the gear thruster on the MTZ 82.1 tractor. The two systems testing showed that the mechatronic module did not obstruct the view and did not hinder the farm tractor steering. The advantage of the proposed module is the ability to quickly switch to manual control, whereas with the gear thruster, it takes time to manually retract the gear between the electric motor and the steering shaft. To install the electromechanical part of the mechatronic module takes half the time compared to the gear thruster, and the farm tractor movement accuracy is 17% higher. This is due to the fact that the "reaction time" of the mechatronic module does not exceed 0.25 seconds. The cost of the developed mechatronic module is 240 thousand rubles, which is comparable to that of the gear thruster.

Key words: Tractor, Precision agriculture, Navigation, Mechatronic module, Thruster, Electric drive, Hardware and software

INTRODUCTION

Due to the navigation systems availability digital technologies are widely used in agriculture, especially in crop production [20; 21]. Precision agriculture can increase production and reduce maintenance costs when operating a farm tractor [22]. Through the use of automatic steering systems, it is possible to achieve farm tractor movement accuracy up to a few centimeters [25, 26].

The satellite navigation systems development has contributed to the rapid transition of agriculture to the digital age. The use of digital technologies in GPS navigation, UAVs, autonomous vehicles, automatic steering systems, etc. can be regarded as a key component of precision farming systems[1]. Due to the navigation systems availability these technologies are widely used in precision farming systems and can improve the efficiency of technological operations on the soil [6; 13; 18; 19]. In addition, production increases, energy costs associated with the farm tractor operation on the field are reduced. The primary goal in precision agriculture is to ensure the accuracy of the farm tractor movement up to a few centimeters by means of navigation satellite systems [23]. Such accuracy can be provided by navigation and automatic steering systems of the farm tractor.

The most common automatic steering system is an electric motor on the farm tractor steering column with a steering wheel drive, without being connected to the steering hydraulic system [8; 11]. This system minimizes or eliminates significant changes in the steering system [12; 17]. At present, the agricultural sector uses automatic steering system firms Klaas (Germany), Trimble (USA), Raven (USA), Topcon (Japan), Agleader (USA), Leica (Switzerland) [3; 16]. Moreover, in different countries innovative enterprises, such as Agjunction LLC [2], OOO («a limited liability company under the laws of Russian Federation») EnergeticheskijSharin cooperation with the federal state budgetary educational institution of higher education "Bashkir State Agrarian University" [15], Deere & Company [4], etc. are developing their own automatic steering systems.

In most of these systems, the electric motor rotates the steering wheel frictionally or by means of a rigid mechanical linkage [14]. This has several disadvantages: clutch slipping, gear wear, chains / belts stretching, fitting complexity, additional efforts on the steering wheel with manual control, etc. Additional mechanical links between the steering wheel and the motor rotor adversely affect the farm tractor control accuracy, reliability and thruster cost.

Taking into account the shortcomings identified in the automatic steering systems, the farm tractor should be equipped with a mechatronic module consisting of two parts: hardware/software and electromechanical. In the hardware and software, the law of the farm tractor motion control is applied according to the navigation system signals [24]. In the electromechanical part, a brushless DC motor with an external rotor is used, the rotor being a part of the steering wheel (Figure 1). To change the rotor position is to turn the steering wheel without intermediate mechanisms. The mechatronic module can increase the speed of the farm tractor control, simplify the design and reduce the thruster cost.

To sum up, commonly used automatic steering systems have a number of significant drawbacks associated with

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Figure 1: The electromechanical part of the farm tractor mechatronic steering module

their design. Thus,the aim of the study is to improve the automatic steering efficiency of a farm tractor through the use of the mechatronic module.

The objectives of the study are as follows:

1. to develop an electromechanical design for the farm tractor steering on the basis of a brushless DC motor with an external rotor;
2. to implement the hardware and software of the farm tractor electric power steering;
3. to create and study the farm tractor mechatronic steering module.

METHODS

Figure 2 shows the functional diagram of thefarm tractor mechatronic steering module. The functional diagram of the developed module consists of the following elements: GPS / GLONASS navigation receiver; steering angle sensor; microprocessor system with a farm tractor control program; electric power steering based on a brushless DC motor.

The sequence of the system operation is as follows. The signals of the navigation receiver in the hardware and software complex set the farm tractor motion trajectory. The steering angle sensor transmits information about the position of the wheels relative to the farm tractor to the tractor motion control program. Based on these signals, the program calculates the value of the transverse

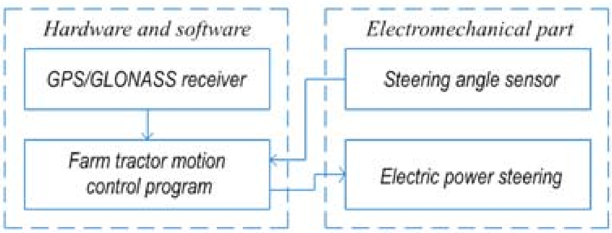

Figure 2: Mechatronic module functional diagram

deviation from the guided path, driving direction and speed, and then, if necessary, rotates the steering wheel to bring the farm tractor to the guided path. This system provides a higher accuracy of movement without an operator involvement.

For the mechatronic module a brushless DC motor is the best type of DC electric drive, since it is similar to a commutator DC motor by its operating principle and performance, and due to the commutator absence, it has high reliability and durability. Speed, torque and reverse are controlled without drive power circuits. This is possible by changing the voltage and the phase advance angle.

The scheme of the electromechanical part of the mechatronic module under study is as follows (Figure 3). The stator 4 of a brushless DC motor is rigidly fixed to the steering column 1 through the stator core flange 2. The steering wheel 10 is rigidly connected to the rotor 7 through the flange 8. The rotor 7 is also fixed to the steering column by means of a rotation bearing 6. The rotary motion of the rotor 7 through the steering wheel 10 is transmitted to the steering wheel shaft 9. The brushless DC motor operates on discrete Hall sensors 5 which are necessary for determining the rotor position 7. To control the engine phases, 6-stroke pair switching is used depending on the signals of the Hall sensors 5.

The farm tractor steeringat large turning radii (the turning radius is much larger than the wheelbase of the farm tractor) is described by the first-order differential equation [5]:

$$T\frac{d\varpi}{dt} + \varpi = k\alpha \quad (1)$$

where T is the time constant, s;

ω - the farm tractor steering rate, rad / s;

k - transfer constant;

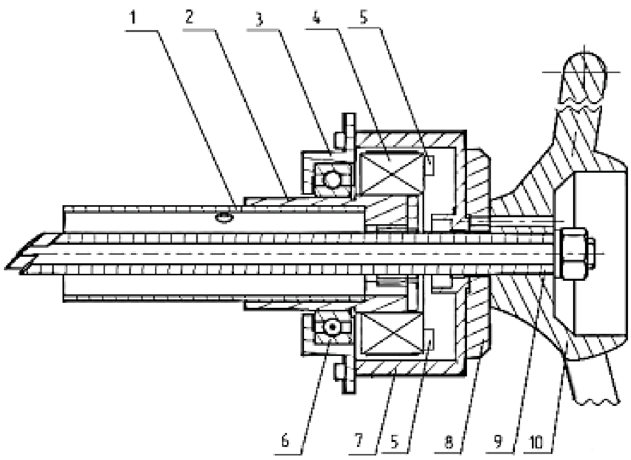

Figure 3: Electromechanical part of the mechatronic steering module with a brushless DC motor: 1 – steering column, 2 – stator core flange,3 –- bearing housing, 4 – stator, 5 – Hall sensors, 6 – bearing,7 – rotor, 8 –- rotor flange, 9 – steering wheel shaft, 10 – steering wheel

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α - control action on the farm tractor steering gear from the mechatronic module, rad / s.

The deviation between the current tractor position and a guided path is determined by navigation signals. The deviation from the guided path is determined by two terms:

$$\Delta Y = Y_0 + L \cdot \Psi \quad (2)$$

where Y_0 – tractor turning center displacement relative to a guided path, m;

L - distance from the tractor turning center to the visible point (forward shift), m;

Ψ - angle between the tractor driving direction and a guided path, rad.

The control action on the farm tractor steering gear from the mechatronic module is regulated by the proportional-integral-derivative (PID) controller depending on the deviation from the set trajectory ΔY.

To describe the movement of the tractor with an agricultural machine we assume that the tractor has rear driving wheels and front steering wheels. The main kinematic parameters of the tractor in motion are shown in Figure 4.

The kinematics of the farm tractor movement is considered through the movement of its basic points [7]. In our work the leading point of the aggregate during self-steering is the middle of the tractor front axle (the point with the GPS/GLONASS antenna being installed), since it responds most quickly to the steering wheels turning.

In Figure 4 the following symbols are used: φ - the deviation angle of the steering tractor wheels (in the normal mode it is proportional to the control action of the mechatronic module on the farm tractor steering mechanism α), rad; *θ* - the angle between the agricultural machine longitudinal axis and the tractor longitudinal axis, rad; Ψ_{tra} Ψ_{mach} - the steering angles of the tractor and agricultural machine, rad; V_{tra}, V_{mach} - the speed of the tractor and agricultural machinery, m/s; a, b, c - tractor linear parameters, respectively: distance from the steering wheels axis to the tractor pivot (Point O in Figure 4), from the tractor pivot to the attaching point of the tractor with the agricultural machine, from the attaching point of the tractor with the agricultural machine to the rotation axis of the agricultural machine, m; ΔS - distance (m) traveled by the tractor in the current direction for an infinitely small period of time Δt; $\vec{W} = \dot{\Psi}_{mach} \cdot \vec{c}$ - linear speed vector of the attaching point of the agricultural machine with the tractor; it is perpendicular to the agricultural machine longitudinal axis and defines the trailed agricultural machine steering rate. According to the aspect ratio of the triangle (Figure 4), the tractor steering angle ($\Delta\Psi tra$), corresponding to Δt, has the following correlation dependence [9]:

$$\Delta\Psi_{mpa} = arctg\frac{\Delta s \cdot tg\varphi}{\Delta s + a} \quad (3)$$

The tractor steering speed is described by the expression:

$$\dot{\Psi}_{tra} = \lim_{\Delta t \to 0}\frac{\Delta\Psi_{tra}}{\Delta t} = \lim_{\Delta t \to 0}\frac{arctg\dfrac{V_{tra}\cdot\Delta t\cdot tg\varphi}{V_{tra}\cdot\Delta t + a}}{\Delta t} = \frac{V_{tra}}{a}tg\varphi \quad (4)$$

It's obvious that

$$\Psi_{tra} = \Psi_{mach} + \theta \quad (5)$$

Agricultural machine speed is determined by:

$$V_{mach} = V_{tra}\left(\cos\theta + \frac{b}{a}tg\varphi\cdot\sin\theta\right) \quad (6)$$

The dynamics of the agricultural machinery angular movement is:

$$\dot{\Psi}_{mach} = -\frac{V_{tra}}{c}\left(\sin\theta + \frac{b\cdot\cos\theta}{a}tg\varphi\right) \quad (7)$$

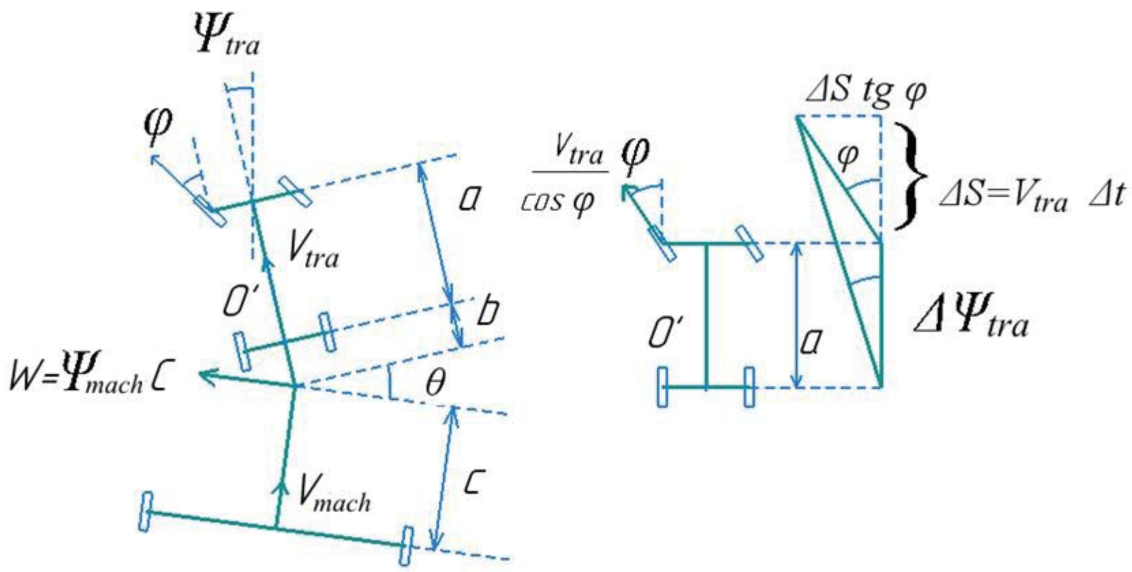

Figure 4: Basic kinematic relations of the aggregate "tractor - agricultural machine"

Equations (4) - (7) describe the dynamics of the "tractor + agricultural machine" aggregate.

To implement the algorithm for modeling the agricultural machine trace, a complex farm tractor movement is considered, in which the farm tractor simultaneously participates both in translational and rotary motion relative to the instantaneous turning center. Figure 5 shows the scheme for constructing the track of a trailed agricultural machine. At a set wheel turning angle φ, the coordinates of the extreme lateral points of the agricultural machine are determined and entered into a two-dimensional data array.

To determine the lateral coordinates of agricultural machine points, the coordinate method [10] was used: where x, y are the current coordinates (according to the GPS / GLONASS receiver) in the fixed coordinate system XOY; *x0, y0* are tractor coordinates in the moving coordinate system X'O'Y '; *xr*, *yr* and *xl* ,*yl* are respectively right and left lateral points of the agricultural machine in the fixed coordinate system XOY.

The coordinates of the tractor instantaneous turning center in the fixed coordinate system XOY can be written as follows:

$$x_{TITC} = -\frac{a}{tg\varphi}\cos\Psi_{tra} + x_0$$
$$y_{TITC} = -\frac{a}{tg\varphi}\sin\Psi_{tra} + y_0 \quad (8)$$

The equation of a straight line passing through the tractor instantaneous turning point and through the middle of the tractor rear axis in a fixed coordinate system is:

$$X\cdot\sin\Psi_{tra} - Y\cdot\cos\Psi_{tra} + y\cdot\cos\Psi_{tra} - x\cdot\sin\Psi_{tra} - a = 0 \quad (9)$$

To determine the equation of the straight line O "M", let us consider the second moving coordinate system X "O" Y " relative to X'O'Y', where the attaching point of the tractor with the agricultural machine is the origin of coordinates. Then the coordinates of the point K in the coordinate system X"O" Y" are equal, respectively, to x''_K =0 and y''_K=0. Therefore, in the XOY coordinate system, the coordinates of the point K are:

$$x_K = (a+b)\sin\Psi_{tra} + x$$
$$y_K = (a+b)\cos\Psi_{tra} + y \quad (10)$$

The coordinates of the point F in the XOY coordinate system are:

$$x_F = a\sin\Psi_{tra} + x - c\cdot\sin\theta$$
$$y_F = -a\cos\Psi_{tra} + y - b - c\cdot\cos\theta \quad (11)$$

The coordinates of the agricultural machine extreme points in the XOY coordinate system are defined as follows:

$$x''_{l,r} = x''_K \pm \frac{d}{2}$$
$$y''_{l,r} = -c \quad (12)$$

These coordinates are entered into a two-dimensional data array to modelan agricultural machine trace.

To implement this mathematical model of the farm tractor movement in software, you must adhere to the following algorithm:

1. Initialization and observation phase:
   -determine current coordinates using the GPS / GLONASS receiver, calculate the starting position;
   -initialize the control system;
   -set the zero position of the steering wheel, calculate the farm tractor driving direction and the initial parameters;
2. Intermediate variables calculation:
   - define all the necessary parameters to implement the law of steering wheel position control (current steering angle, direction and speed);
   -check the current steering angle;
3. Implementation of the steering control law:
   - implement a maneuver of approaching the tractor to the calculated motion path within a set time on the basis of the previously computed parameters;
4. Verification:
   - compare the current angle of the steering wheel with the calculated value and go to step 2 if the end of the trajectory is not reached.

To implement this algorithm, an object-oriented programming language C # was chosen, which is based on the Microsoft.NET Framework. The program was written in a visual development environment of Visual Studio 2018. The farm tractor control program contains a subprogram that automatically plots the optimal route across the field, taking into account the type of tractor, towed or mounted equipment. This subprogram visually displays the movement pattern, the tractor current position, the field being processed with its borders in the graphical user interface (Figure 6).

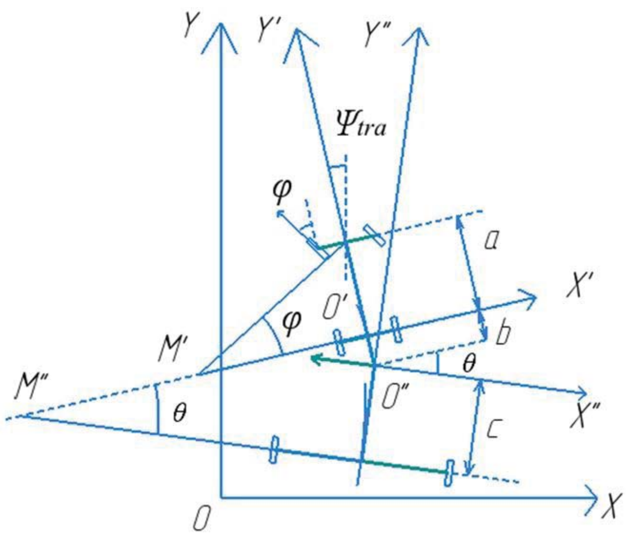

Figure 5: The chart of agricultural machine trace

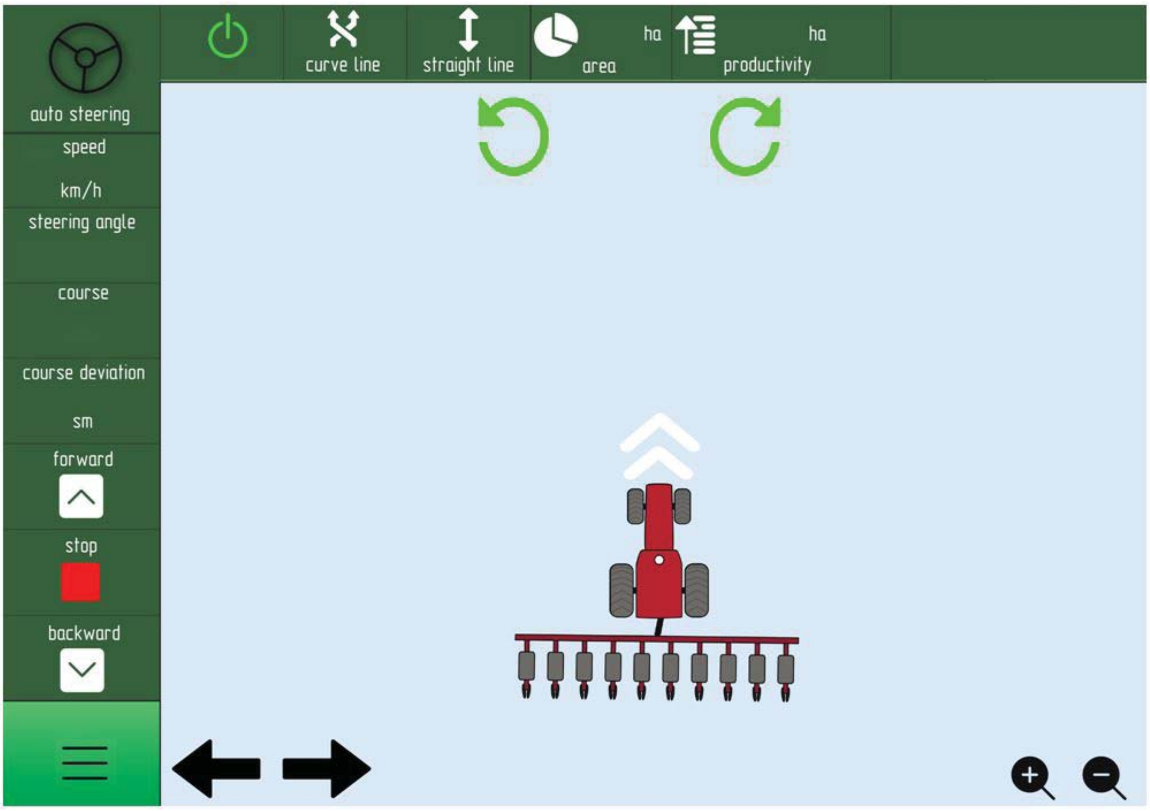

Figure 6: Graphical interface of the farm tractor control program

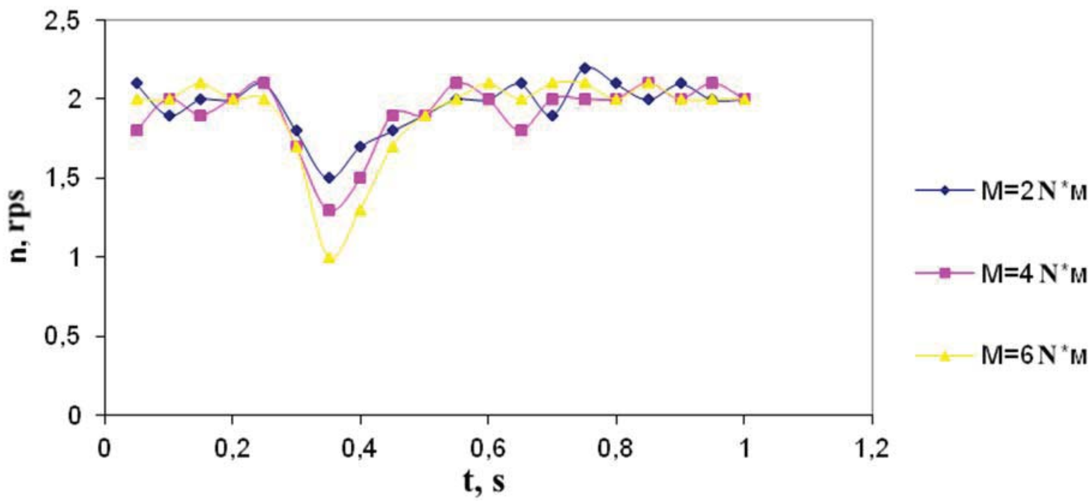

Figure 7: Dynamic dependence of the brushless DC motor rotor speed at different values of the braking torque on the steering mechanism.

RESULTS AND DISCUSSIONS

The parameters of the brushless DC motor PID controller have been selected. As a result of determining the PID controller coefficients, the optimal operation mode of the mechatronic module brushless DC motor was obtained. The graph of the dynamic dependence of the brushless DC motor rotor speed shows that at different drag force values on the steering wheel, the rotor speed is stabilized at the desired value for no more than 0.3 seconds, from the moment the braking force is applied at different values (Figure 7).

The graph in Figure 8 shows that the “reaction time” of the system in question is no more than 0.25 seconds, which is more than enough for thrusters.

Two automatic control systems of a farm tractor (a mechatronic module and a gear thruster [7]) were tested for deviations from the movement pattern on a field of 600 m long (Figure 9).

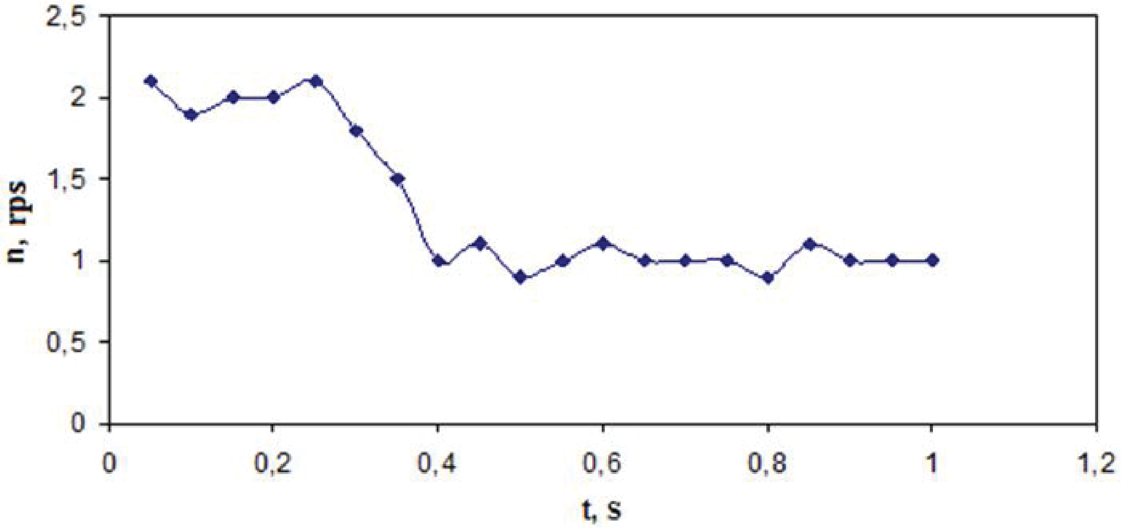

Figure 8: Example of the transient process of changing a brushless DC motor rotor speed during steering

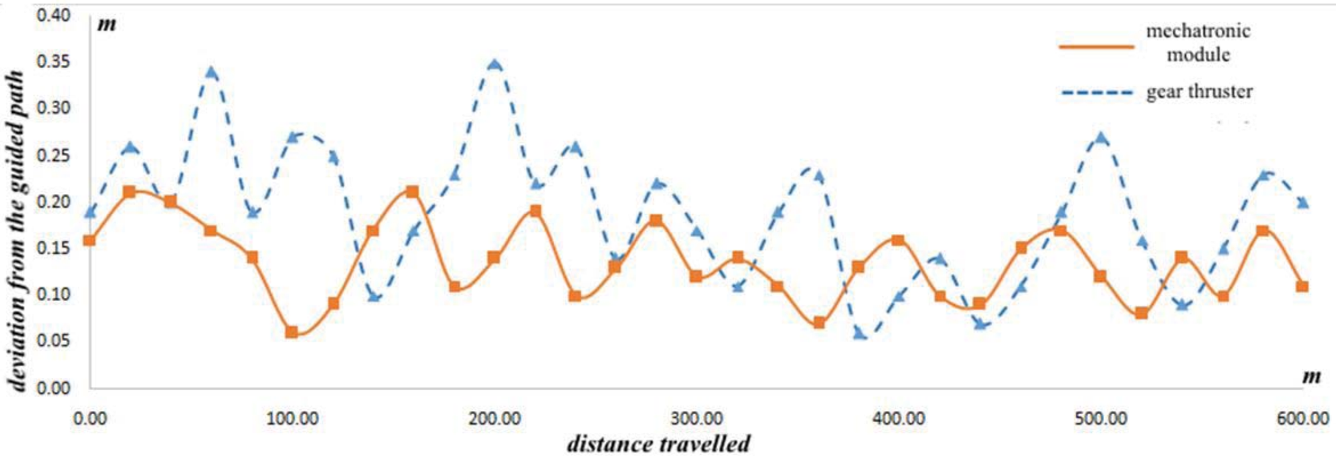

Figure 9: Deviation from the guided path of the farm tractor with the mechatronic module and the gear thruster

As it is clear from the graph, the average deviation from the guided path of the farm tractor with the mechatronic module is 17% less than with the gear thruster.

To prove the hypothesis of improving the efficiency of the farm tractor automatic steering by means of developing and using mechatronic module based on the brushless DC motor with an external rotor, the tractor automatic steering has been compared to the gear thruster in performance. These devices were developed by the innovative company OOO(«a limited liability company under the laws of Russian Federation») EnergeticheskijShar.

The tests were carried out on the tractor MTZ 82.1 at the state unitary agricultural enterprise "Bashselkhoztekhnika". The two systems testing showed that the mechatronic module did not obstruct the view and hinder the farm tractor steering. The advantage of the mechatronic module is the ability to quickly switch to manual control, whereas with the gear thruster, it takes time to manually retract the gear between the electric motor and the steering shaft. To install the electromechanical part of the mechatronic module takes half the time compared to the gear thruster. The farm tractor movement accuracy is 17% higher compared to the thruster based on the reduction electric drive. This is due to the fact that the “reaction time” of the mechatronic module does not exceed 0.25 seconds. The systems performance reliability was not evaluated, but it can be assumed that the mechatronic module reliability is higher as it has a smaller number of structural components. The cost of the developed mechatronic module is 240 thousand rubles, which is comparable to that of the gear thruster.

CONCLUSION

A mathematical model has been developed that describes the movement of the tractor together with the agricultural machine. On the basis of this model the farm tractor motion control algorithm has been created and the mechatronic module hardware and software which can be used as a tractor direction indicator has been implemented. The mechatronic module introduction for the farm tractor control by means of navigation systems reduces maintenance costs (for seeds up to 15%, for chemicals and fuel not less than 10%), reduces a driver fatigue and increases labor productivity (the ability to work at night, as well as in conditions of poor visibility). Simple thruster mounting ensures its quick installation on any domestic and imported equipment. The advantage of the proposed module is the ability to quickly switch to manual control, whereas with the gear thruster, it takes time to manually retract the gear between the electric motor and the steering shaft. To install the electromechanical part of the mechatronic module takes half the time compared to the gear thruster, and the farm tractor movement accuracy is 17% higher. This is due to the fact that the “reaction time” of the mechatronic module does not exceed 0.25 seconds. The cost of the developed mechatronic module is 240 thousand rubles, which is comparable to that of the gear thruster. The practical and scientific significance of the work is the developed mechatronic module for the farm tractor steering, in which brushless DC motor with an external rotor is used as an electric drive. The system provides the accuracy of the farm tractor movement up to 20 centimeters.

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