Study of the steering of a wide span vehicle controlled by a local positioning system

Volodymyr Bulgakov,[1] Simone Pascuzzi,[2] Semjons Ivanovs,[3] Volodymyr Kuvachov,[4] Yulia Postol,[4] Francesco Santoro,[2] Viktor Melnyk[5]

[1]Department of Mechanics, Faculty of Construction and Design, National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine; [2]Department of Agricultural and Environmental Science, University of Bari Aldo Moro, Bari, Italy; [3]Faculty of Engineering, Latvia University of Life Sciences and Technologies, Jelgava, Latvia; [4]Tavria State Agrotechnological University, Melitopol, Ukraine; [5]Kharkiv Petro Vasylenko National Technical University of Agriculture, Ukraine

Abstract

Controlled traffic farming allows to minimize traffic-induced soil compaction by a permanent separation of the crop zone from the traffic lanes used by wide span tractors. The Authors developed an agricultural wide span vehicle equipped with a skid equipment for turning and an automatic driving system prototype based on a laser beam. The aim of this work was to study the kinematic conditions that control the steering of this machine. Furthermore, the accuracy and the maximum delay time of the signal transmission by the automatic driving system of the set-up was also assessed. In comparison with crawler tractors, the turning of the agricultural wide span vehicle needs a smaller difference in the moments applied to its right- and left-side wheels. For the predetermined accuracy of the beam position relative to the plant rows, $\pm d_s = \pm 0.025$ m, the accuracy of the direction of the laser beam at a distance S=200 m should not be more than ±0.07° and ±0.0014°, considering a run length of 1000 m. Furthermore, at a speed V=2.5 m s^{-1} a trajectory deviation $\varphi \leq 5°$ requires a topmost delay time of the control signal of Δt_{max}=0.11 s is required.

Introduction

Controlled traffic farming (CTF), in which the crop zone is distinctly and permanently disjoined from the permanent traffic lanes, represents a good strategy to reduce traffic-induced soil compaction (Hamza *et al*., 2005; Keller *et al*., 2019). CTF lends itself to the use of wide span tractors or gantry systems, which are certainly more convenient than traditional tractors and machine-and-tractor aggregates (Onal, 2012). In this regard, the practical experience of using bridge tractors in various countries has shown the following advantages: energy saving during soil cultivation has been as high as 55%; the cost of sowing crops has decreased by 40%; the quality of tillage and soil structure ha improved; area losses for travelling of agricultural machinery have been minimized; high accuracy of tool positioning has been achieved; agricultural operations has been automated; crop yields have increased by 7-10% (Raper, 2005). A wide span tractor usually works over tilled crops, and often implements rigidly linked to it operate on rows in which plants are located (Chamen, 1992). On the other hand, gantry systems, due to their large wheel track width, during their motion along the traffic lanes, can undergo trajectory deviations caused by different factors, such as the unevenness of the soil resistance, the type of driving wheels, forward speed, acting forces and so on (Bulgakov *et al.*, 2019c), which can affect the working organs and damage the plants (Bulgakov *et al.*, 2019b; (Bulgakov *et al.*, 2019a). Wide span tractors can also be equipped with automatic driving systems. Traditionally, an automatic control (regulation) system is a closed dynamic system in which the difference between the pre-set and the current values of the adjustable parameter is measured (Ji and Zhou, 2014; Chebrolu *et al.*, 2017). Depending on the result of the measurement, an automatic action is performed, aimed at reducing the indicated difference to an admissible small value (Bulgakov *et al.*, 2020). As is known, the task of automated driving vehicles is to perform guide actions without any operator's intervention (Yang *et al*., 2015). This task, applied to a wide span tractor moving along the tracks of traffic lanes, turns out to be fairly complicated due to the relatively small possibilities for manoeuvring it, when in motion, as well as the impact of a large number of random disturbing factors. Indeed, these can create many possible situations which need to be countered by the impact of the interrelated means of control (steering control, brakes, engine control, *etc*.) (Bulgakov *et al.*, 2018).

GNSS-based systems are the most popular for the automatic driving of mobile agricultural machinery (He *et al.*, 2011; Luo *et al.*, 2009). In this regard, the technical perfection of modern equipment in terms of the accuracy of reproducing set trajectories of mobile machines is astonishing considering the results achieved (Griepentrog, 2009). Yet, the accuracy of GPS equipment is insufficient for the implementation of fully automated driving in wide span tractors within permanent traffic lanes. Attempts to supplement GPS navigation systems with additional corrective short-

Correspondence: Simone Pascuzzi, Department of Agricultural and Environmental Science, University of Bari 'Aldo Moro', via Amendola 165/A, 70126 Bari, Italy.
Tel./Fax: +39.080.5442214. E-mail: simone.pascuzzi@uniba.it

Key words: Traffic farming; agricultural wide span vehicle; automatic driving; local positioning systems; accuracy.

Contributions: the authors contributed equally.

Received for publication: 7 January 2021.
Accepted for publication: 25 May 2021.

Journal of Agricultural Engineering 2021; LII:1144
doi:10.4081/jae.2021.1144

range navigation systems complicated significantly the equipment, reduced its reliability and increase its cost (Zhu *et al.*, 2016; Bakker *et al.*, 2011).

The Authors designed and developed an electric traction agricultural wide span vehicle, which is able to move within the tracks of permanent traffic lanes and to turn by modifying the wheel speeds of the machine sides. For such a machine it would be interesting to be able to control automatically its motion along a predetermined trajectory of the tracks of permanent traffic lanes, using local positioning systems. Therefore, the Authors set up and implemented an automatic driving system prototype based on a laser beam.

The Authors investigated in enough depth both theoretical and practical aspects of the use of agricultural wide span vehicles in previously published articles. According to the results of these studies, the design and technological schemes have been substantiated for the units based on mobile bridge agricultural machinery, which can ensure that they are adequately controllable and stable and can move smoothly. Conversely, the research of driving automation of the agricultural wide span vehicle was addressed by the Authors for the first time.

The design of a mobile bridge agricultural equipment based on the main indicators must be consistent with the parameters of the coordinate-transport system of the field, its placement on the headland, and the possibility of implementing their movement in an automatic or semi-automatic mode. Considering the relevance of using agricultural wide span vehicles, conceptual decisions should be adequately substantiated for their individual components, such as the choice of navigation system, running system, controls, power plant. The success of further automation in agricultural wide span vehicles and the entire agricultural bridge complex depends on the right choice of design schemes and these elements. Therefore, in the first part of this paper, the Authors are proposing a condition for controlling the skid steering of the machine in relation to the difference of moments brought to the right and left side. In the second part, using the example of the laser system for tracking the trajectory of the machine, the magnitude of the orientation error (accuracy) is substantiated with reference to a turn of the frame when entering the turn, which should be eliminated when the machine exits the turn.

Materials and methods

The agricultural wide span vehicle

The agricultural wide span vehicle is a customized device conceptualized and developed by the Authors. It consists mostly of a steel frame which supports the following main parts: two electric motors, power transmission, undercarriage, control mechanisms, and implement interface (Figure 1). The undercarriage is a substructure which holds up four semi-axes on which wheels with tyres, each of a standard size 9.5R32, are fixed.

Each of the Energolukss SIA AIR80B6 (Energolukss, SIA, Riga, Latvia) electric motors has the following main features: asynchronous 3-phase type, frequency of 50 Hz, rated voltage of 380 V, and rated power of 1.1 kW. In the prototype stage, the power supply for the electrical motors is provided by using a suitable cable connected to a 3-phase power generator carried by the vehicle itself. The electric motors are placed on the right and left sides of the agricultural wide span vehicle. They drive the left and right wheels by means of chains and gear transmissions, so that they move along the tracks of permanent traffic lanes. The change in direction is obtained by adjusting the rotational speeds of the wheels, *i.e.* through a skid steering system (ISO, 2008). The implement interface is formed by a mounted three-point hitch to which agricultural machines and implements can be aggregated to the wide span vehicle.

The main technical characteristics of the agricultural wide span vehicle are: i) operating mass of 1158 kg; ii) pulling force (over stubble of crops) of 6.3 kN; iii) wheel track width of 3.5 m; iv) wheelbase of 2.3 m.

Theoretical considerations

As a result of numerous experimental studies and observations, the Authors found that, in order to correct automatically the motion direction of an agricultural wide span vehicle, in particular for rectilinear motion within a constant technological track, it must be able to make both turns and plane-parallel shifts of the machine frame relative to the trajectory of motion.

When a four-wheeled machine turns with a sideways turn pattern, the lateral displacement of the machine relative to the trajectory line is only possible because of uncontrolled sideways drift.

Figure 1. The wide span vehicle during the test: 1 - frame; 2 - electric motors; 3 - permanent traffic lanes.

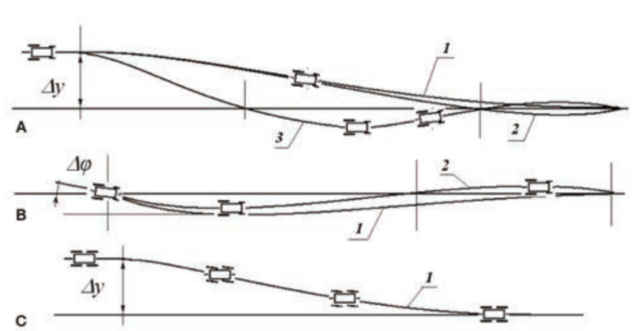

Figure 2. Correction of trajectory disturbances. A) and C) parallel displacement of the machine; B) rotation of the machine axis without offset; 1 - aperiodic trajectory of the transient process; 2 - trajectory in case of overregulation; 3 - trajectory at damped auto-oscillations of the controlled variable.

Correcting the trajectory of machines with this turning pattern is accompanied by a degradation of the machine orientation relative to the set trajectory (Figure 2A curve 1 and 2C).

When the steady motion of the machine is disturbed by a parallel displacement Δy of the machine axis relative to a given trajectory (Figure 2A), the control system must turn the machine axis in the opposite direction to the displacement (entering the turn). Then, after some time (the turn itself), which is determined by the speed of motion, it should turn again the machine axis, but in the opposite direction (exit from the turn).

In another situation, in which the disturbance occurs in the form of a rotation $\Delta\varphi$ of the machine axis without its centre displacement relative to the line of the given trajectory (Figure 2B), the correction of the position requires some way of entering the turn such that the machine will move from the line of the given trajectory during the following turn of the frame in the opposite direction and then exit the turn, again by turning the frame.

When the control of a machine is automated, there is a discrepancy between the speed of action of the control mechanisms and the speed of action of the disturbing factors. Over-regulation or even damped oscillations of the regulated quantity are likely to occur (curves 2 and 3 in Figure 2A, respectively).

If the current position of the machine is indicated by signals proportional to displacement Δy and rotation $\Delta\varphi$ of the frame, the maximum efficiency of automatic driving will be provided by a control system that allows both a lateral plane-parallel movement of the machine to correct parallel displacements from a given trajectory and a straight-line movement of the machine with simultaneous rotation around the vertical axis to correct angular deviations.

In this respect, the analytical study of the automatic driving process of the agricultural wide span vehicle has been carried out considering its skid steering system. Referring to this, first its equivalent circuit was constructed. Also, an analysis was conducted on the scheme of the steering of the agricultural wide span vehicle in a horizontal plane X_aQY_a (Figure 3), which is implemented based on the different speeds of its left and right wheels.

As is known, in the driving mode, the following forces act on each wheel of radius r of the agricultural wide span vehicle (Figure 4): the vertical load N, the tangential force F_D and the reaction of the wheel axis F_T, the turning torque M_k and the rolling resistance moment M_f, which is made up of action force N and reaction force N_f, and the lateral force T (Figure 3) (Wong, 2001). When the wheel, loaded with a lateral force T, rolls in a direction x at a speed V_x, a deformation of the tyre takes place in the lateral direction, which leads to a lateral slip of the tyre, that corresponds to the appearance of the speed component V_y.

To overcome the turning resistance forces to the right and left wheels of the agricultural wide span vehicle (Figure 4), different turning torques M_{ki} must be applied, which will provide different values of the tangential forces F_{Di}:

$$F_{Di} = \frac{(M_{ki} - M_{fi})}{r_i}, \tag{1}$$

where: M_{ki} is the turning torque applied to the i-th wheel; r_i is the dynamic radius of the i-th wheel; M_{fi} is the rolling resistance moment of the i-th wheel.

Due to the difference in the sum of the driving moments M_k applied to the left and right wheels of the agricultural wide span vehicle, a torque M_p appears in a horizontal plane resulting from:

$$M_p = \frac{1}{2}K(F_{Dl1} + F_{Dl2} - F_{Dr1} - F_{Dr2}) \neq 0, \tag{2}$$

where: F_{Dl1}, F_{Dl2} and F_{Dr1}, F_{Dr2} are the tangential forces applied, respectively, to the front and rear wheels of the left and right sides of the agricultural wide span vehicle; K is the track width.

The appearance of the torque M_p causes a change in the direction of the agricultural wide span vehicle. The turning resistance of the machine leads to the appearance of the torque of the lateral interaction forces of the wheels with the supporting surface M_T, which can be considered as a stabilising torque, and the moment of inertia M_j:

$$M_p = M_T + M_j = \frac{1}{2}L(T_{l1} + T_{r1} - T_{l2} - T_{r2}) + J_m\left(\frac{d^2\varphi}{dt^2}\right) \tag{3}$$

where: M_T is the torque caused by the lateral interaction forces of

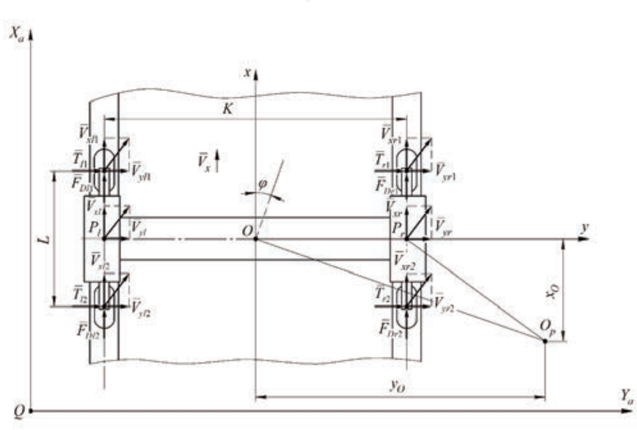

Figure 3. Kinematics of the steering of the agricultural wide span vehicle.

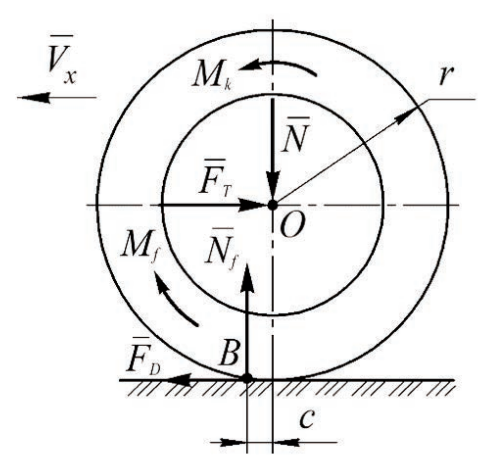

Figure 4. A scheme of forces and torques acting upon the wheel of the agricultural wide span vehicle in the driving mode.

the wheels with the supporting surface; M_j is the moment of inertia; T_{l1}, T_{l2} and T_{r1}, T_{r2} are the lateral forces applied, respectively, to the front and rear wheels of the left and right sides of the agricultural wide span vehicle; J_m is the moment of inertia of the agricultural wide span vehicle in a horizontal plane; $\frac{d^2\varphi}{dt^2}$ is the angular acceleration of the agricultural wide span vehicle in a horizontal plane, which occurs when entering the turn and leaving the turn, and is equal to zero when the turn is stable, *i.e.* when turning with a constant radius.

When the turn is stable, the following equality is satisfied:

$$\frac{1}{2}K(F_{Dl1}+F_{Dl2}-F_{Dr1}-F_{Dr2})=\frac{1}{2}L(T_{l1}+T_{r1}-T_{l2}-T_{r2}) \tag{4}$$

hence:

$$(F_{Dl1}+F_{Dl2}-F_{Dr1}-F_{Dr2})=\frac{L}{K}(T_{l1}+T_{r1}-T_{l2}-T_{r2}) \tag{5}$$

The steering of the agricultural wide span vehicle is obtained by means of the difference in the moments applied to the right and left wheels. Equation (5) shows that the difference in moments required for the turning of a crawler tractor, which has a similar turning method to the agricultural wide span vehicle, is greater than the corresponding value for the agricultural wide span vehicle, due to the larger wheel track width and the relatively smaller wheelbase of this last machine (Abe, 2015). On the contrary, according to Equation (5), it makes the actual rotation possible using the skid-steering system for wide-track axle agricultural tractors.

In the local coordinate system xOy, which relates to the agricultural wide span vehicle (Figure 3), the position of the instantaneous turning centre O_p determines the relative speeds of the wheels in the coordinates X_aQY_a. Therefore, for the conditional centre P_l in the middle of the left-side wheels of the agricultural wide span vehicle, the values of the velocity components V_{xl} and V_{yl} can be found using:

$$V_{xl}=\frac{d\varphi}{dt}\left(y_0+\frac{1}{2}K\right) \tag{6}$$

And

$$V_{yl}=\frac{d\varphi}{dt}x_0 \tag{7}$$

where $\frac{d\varphi}{dt}$ is the angular turning velocity of the agricultural wide span vehicle in a horizontal plane.

In a similar way, the values of the velocity components V_{xr} and $V_y{}^r$ can be found for the conditional centre P_r in the middle of the right-side wheels of the agricultural wide span vehicle using:

$$V_{xr}=\frac{d\varphi}{dt}\left(y_0-\frac{1}{2}K\right) \tag{8}$$

And

$$V_{yr}=\frac{d\varphi}{dt}x_0 \tag{9}$$

If the sizes and elastic properties of the left and right tyres are identical and the tyres interact with the supporting surface of the tracks of permanent traffic lanes when a moment is applied to the agricultural wide span vehicle in a horizontal plane, then equations (7) and (9) highlight that the same lateral deformations will be observed for the tyres of any given side. This implies that the tyres have equal speeds, but opposite directions, thus causing the lateral skidding of the tyres and their speeds in the transverse direction, that is $V_{yl1}=-V_{yl2}$ and , $V_{yr1}=-V_{yr2}$. The indicated equality of velocities is possible only at $x_0 = L/2$. Therefore, the point of the instantaneous turning centre of the agricultural wide span vehicle should always be on the axis of the transverse symmetry of its undercarriage.

The result obtained for the position of the instantaneous centre of rotation on the transverse symmetry axis of the wide-span agricultural vehicle is useful for the implementation of the proposed method of driving automation. Indeed, it is known that the skid steering system mounted on a vehicle with rigid axles makes it impossible to perform transverse motions of the machine without rotations. This means that a turn by a skid steering system does not allow to correct the trajectory by a lateral displacement of the machine longitudinal axis, in which the instantaneous centre of rotation is on the longitudinal axis of symmetry. In the case of a displacement of the machine from a given trajectory (for example, due to motion in a cross slope), the recovery of the given trajectory will be performed by a rotation of the machine axis, and will require subsequent correction by turning in the opposite direction.

Experimental tests

As is known, any automatic motion system for mobile machines must reproduce the given trajectory of motion (regulated parameter) by steering control (regulating body), compensating all deviations from the course, caused by the action of perturbing factors. In its classical formulation, the problem of automating the driving of mobile machines is reduced to the task of creating a set of devices that can perform the actions described above without the participation of the operator. This problem with respect to ground mobile machines, including bridge machines, turns out to be quite difficult, primarily because of the difficulty of orientation. During the movement of a mobile bridge vehicle, the action of a large number of random disturbing factors creates many possible situations, which need to be managed by controlling a number of interrelated controls (steering, brakes, engine control, *etc*.). In this respect, experimental tests were carried out in a specially equipped laboratory aimed at implementing and analysing the results of the proposed method based on a laser beam for the automatic driving of the agricultural wide span vehicle along the tracks of permanent traffic lanes. The use of a laser beam (or a different type of beam) can represent, in our opinion, a useful approach to stabilize automatically the trajectory of the agricultural wide span vehicle fitted with a skid steering system along the tracks of permanent traffic lanes. Unlike for the well-known laser beam-based driving system, the path of the agricultural wide span vehicle may be determined directly based on two fixed lines, which are the outer edges of the pair of permanent traffic lanes (Bakker *et al*., 2011).

The equipment for setting up the laser beam for the motion trajectory of the agricultural wide span vehicle and its automatic driving along the tracks of permanent traffic lanes was implemented in the following way.

Two red LG-004RG laser emitters (LG, China) (1 and 2 in Figure 5) were each fixed on a tripod. One tripod was placed at the beginning of the run on the left edge of the permanent traffic lanes and the other at the beginning of the run on the right edge (points A_1 and A_2 in Figure 5A). The arrangement of the laser emitters was precisely oriented horizontally relative to the tracks of the permanent traffic lanes. These laser beams created two optical lines, which represented the boundary within which the agricultural wide span vehicle had to move along the permanent traffic lanes. The main technical features of the LG-004RG laser emitters were the following: wavelength range/CCT of 635 nm-670 nm, maximum beam distance of 1000.0 m, and output power of 5mW. Two target FD-263 photodetectors (Elektro Mag, Rovno, Ukraine) (3 and 4 in Figure 5) were each fixed on a tripod. One tripod was placed at the end of the run on the left edge of the permanent traffic lanes and the other at the end of the run on the right edge (points B_1 and B_2 in Figure 5A). Each photodetector consisted of an array of photodiodes and each photodiode had a 3×3 mm photosensitive element.

When the agricultural wide span vehicle was in motion, the external disturbances acting on it tended to deviate it from the preset rectilinear trajectory. In this case, the boundaries of its left-side and right-side displacements were the outer edges of the permanent traffic lanes.

These edges are represented in Figure 5A by the lines A_1B_1 and A_2B_2, respectively. If a deviation from the preset trajectory of the agricultural wide span vehicle in motion occurred so that its outline intersected any of these lines, a signal was generated and sent to the corresponding electric motor then, depending on which (left or right) photodiode stopped receiving a laser beam. This electric motor modified the revolutions in the wheel drive of one of the sides of the agricultural wide span vehicle. Therefore, if, for instance, the agricultural wide span vehicle blocked with its right wheels the supply of the laser beam to the right photodetector (*i.e*. crossing of the line A_2B_2 occurred), then its shift took place to the right. In such a case, the automatic system changed the revolutions of the wheels of its left-side drive. After the restoration of the supply of the laser beam to the photodetector, the rectilinear movement of the agricultural wide span vehicle was resumed. The diagram of the electrical principle behind the automatic control of the movement of the agricultural wide span vehicle is shown in Figure 6. In detail, Figure 6A shows the connection of the two electric motors of the agricultural wide span vehicle that transmitted power to the drives of its left and right wheels, respectively. The scheme of the automated driving control of the agricultural wide span vehicle, using the radiation-photodetector sensors, is shown in Figure 6B.

The agricultural wide span vehicle, moving along the tracks of the permanent traffic lanes, covered a path of 200 m at the speed of 2.0 m s^{-1} and the following parameters were recorded: i) the oscillations between the on *vs* off supply of the electric motor (control action oscillations) that drove the corresponding wheels of one side of the machine, which were strictly related to the fluctuations of the tangential forces F_{Di}; ii) the bearing angle φ of the agricultural wide span vehicle. The test was repeated three times on the same tracks.

The relative bearing angles φ of the turning of the agricultural wide span vehicle in the horizontal plane was measured through the 3-Axis gyroscope module GY-521 (InvenSense Inc, San Jose, California, USA, having a measurement range of ±200° s^{-1}. This gyroscope module GY-521, which was placed on the frame of the agricultural wide span vehicle close to the longitudinal coordinate of its centre of mass, was connected to a laptop via the L-CARD model E14-140-M (Moscow, Russian Federation) converter carrying a 32 bits processor and 8 differential input channels. The converter also received the electrical feeding and no feeding signal from the digital volt-ampere meter AC130-250V placed in the control block of the agricultural wide span vehicle. An ad hoc software was used to evaluate the time of supplying and stopping the elec-

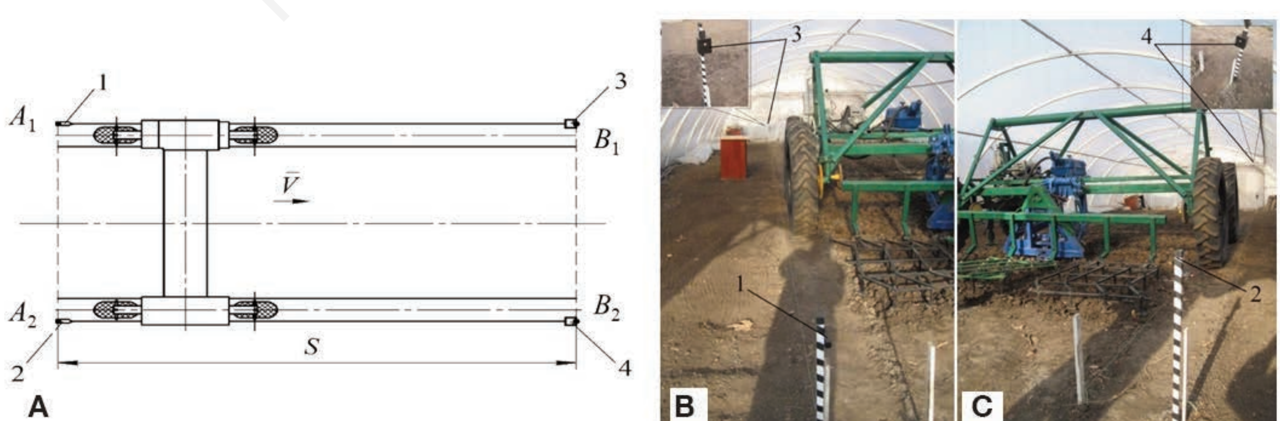

Figure 5. A) The driving scheme of the agricultural wide span vehicle based on the laser; B) arrangement of the equipment for the laser along the trajectory on the left side of the vehicle; C) the same equipment on the right side of the vehicle. 1, 2 - the emitters; 3, 4 - the receivers.

tric motor of the wheel drive of one of the boards. In particular, the stopping time was considered as restoration time of the straight-line motion of the machine due to the deviation from it. Therefore, this electric supplying and stopping time determined fluctuations in the automatic driving system of the agricultural wide span vehicle. The obtained experimental data were statistically processed to evaluate frequency, dispersion, normalized spectral density concerning the fluctuations of both the tangential forces F_{Di}, and the bearing angle φ. As is known, the analysis of the dispersion of fluctuations, which characterises a random oscillatory process as this under study, can be performed in the frequency domain through the spectral densities (Park, 2018).

Results and discussion

The analysis of the spectral densities highlighted that, during the motion of the skid steering wide span vehicle along the tracks of permanent lanes, the oscillations related to the tangential forces F_{Di}, had a low frequency (Figure 7). The basic spectrum of these dispersions was concentrated in a range of frequencies from 0 to 2.0 s^{-1}, that is from 0 to 0.5 Hz. The dispersion of the oscillations of the bearing angle φ was also concentrated in almost the same frequency range (Figure 7). The standard deviation of the fluctuations of this parameter was ±0.014 radians. As is known, this statistical parameter estimates the variance of the bridge vehicle deviations from the straight-line trajectory during its movement. The smaller the variance of the angular deviations of the agricultural vehicle, the more organized the system of its automatic driving along the tracks of permanent lanes.

Since the main spectrum of dispersions of these oscillations was focused on low frequencies (Figure 7), only the high accuracy of the system of its automated driving on the tracks of permanent lanes using a laser beam made it possible for it to be adequately controllable.

The test for the automatic driving process of the agricultural wide span vehicle, when in motion along a straight trajectory, showed that it is necessary to fix two points on both sides of the field at a distance S apart in order to achieve a high pointing accuracy of the laser beam (Figure 5). If the emitter is installed at point A_1, the beam must hit point B_2 with a preset accuracy $\pm\delta_s$ to achieve the fixed driving precision of the agricultural wide span vehicle. Therefore, the following condition for the position accuracy of the emitter $\pm\Delta_\alpha$ had to be met:

$$\Delta\alpha \leq arctan\left(\frac{\pm\delta_s}{s}\right) \tag{10}$$

where $\pm\delta_s$ is the preset accuracy of the laser beam sent by the emitter and S is the length of the run.

Equation (10) is illustrated in Figure 8. As to the predetermined accuracy of the beam position relative to the rows of plants $\pm\delta_s$ = ±0.025 m, the accuracy of the direction of the laser beam at a distance S=200 m should not exceed $\pm\Delta_\alpha$ = ±0.07°. If the distance S is increased to 1000 m, the value $\pm\Delta\alpha$ decreases by 80% to $\pm\Delta_\alpha$ = ±0.0014°. Such an accuracy can be achieved by using special laser emitters with higher accuracies or by equipping the agricultural wide span vehicle with a 'near' navigation system, which fixes the position of the landmarks connected with the traffic lanes. The second method complicates the automation system of the movement and significantly increases the cost of the agricultural wide span vehicle.

When the preset accuracy of the laser beam sent by the emitter is decreased by half ($\pm\delta_s$ = ±0.05 m), the required accuracy of the position of the emitter decreases proportionally by half (Figure 8).

For the agricultural wide span vehicle to steer at the predetermined position accuracy of the preset beam$\pm\delta_s$, when moving in a straight line at a constant speed V, the topmost delay time Δt_{max} of the control signal of its automated control system should be equal to (Figure 8):

$$\Delta t_{max} = \frac{\pm\delta_s}{V\cdot sin\varphi} \tag{11}$$

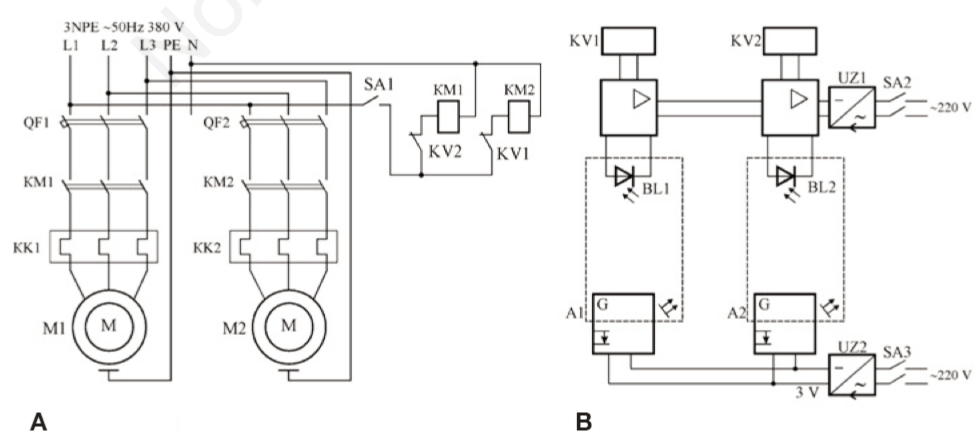

Figure 6. The schematic diagram of the principle behind the automatic driving control of the agricultural wide span vehicle: A) the power unit; B) the automated control system. L1, L2, L3, phase conductors; PE, protection wire; N, zero wire; M1, M2, left and right running electric motors; QF1, QF2, automatic switches; KM1, KM2, magnetic starters; KK1, KK2, thermal relays; SA1, SA2, SA3, switches; KV1, KV2, intermediate relays; UZ1, UZ2, power supply (conversion of AC to DC voltage); BL1, BL2, laser light photoreceiver; A1, A2, laser optical device; G, laser conversion source.

As an example, a trajectory deviation $\varphi \leq 5°$ requires Δt_{max}=0.11 s at a speed V=2.5 m s^{-1} (Figure 9).

With a decrease in the speed of motion V of the agricultural wide span vehicle from 2.5 m s^{-1} to 1 m s^{-1}, the maximum possible time Δt_{max} increases exponentially, which is desirable for a more stable operation of the automated control system. At a speed of motion V of about 1 m s^{-1}, however, this delay time Δt_{max} should not be more than 0.3 s. Therefore, the automatic trajectory control, which was implemented on the agricultural wide span vehicle for its automatic driving, proved to be more stable at the low speeds of the vehicle's motion.

If the directional stability of the motion of the agricultural wide span vehicle is such that the amplitude of its angular oscillations φ reaches 12°, then, according to Equation (11), the time Δt_{max} will decrease by about 16% (Figure 9). This entails more stringent requirements for the operation of the automatic control system.

Some challenges have to be faced in the implementation of our proposed method of automatic driving of the agricultural wide span vehicle along a couple of permanent traffic lanes by means of emitters and target photodetectors located at opposite ends of the field. For instance, after each transit, the emitter-photodetector system needs to be rearranged in the adjacent traffic lanes for the next passage. Therefore, for full automation of the operation of the agricultural wide span vehicle in the field, each couple of traffic lanes should be equipped with its own emitter-photodetector sensors. Despite the costs that may be incurred as a result of the equipment in the field with such systems, an important advantage of our proposed method for an automatically driven bridge agricultural implement is the lack of a GPS system for this purpose.

Conclusions

An analysis was made of the automatic driving system of an agricultural wide span vehicle along permanent traffic lanes, using a laser beam, which changes direction by the adjustment of the rotational speeds of the wheels. Theoretically, significant advantages have been confirmed for this steering system of this type of machine compared to the similar method of turning of a crawler tractor. The turning of the agricultural wide span vehicle requires a significantly smaller difference in the moments applied to its right- and left-side wheels, due to a larger wheel track width and a relatively smaller wheelbase. From the point of view of the lowest energy consumption, the implementation of the aforesaid turning method of the agricultural wide span vehicle is possible if the velocity vectors of its left and right-side wheels are equal and opposite in direction, *i.e.* the turning of the agricultural wide span vehicle should be carried out in such a way that the instantaneous centre of its turning is on the axis of the transverse symmetry of its undercarriage. The automated driving process of the agricultural wide span vehicle along permanent traffic lanes was developed and tested by the Authors, using a laser beam. This process has made it possible to determine the accuracy of the position of the laser beam emitter at a value of 0.0014° and a run length of 1000 m.

The proposed method is very useful where GPS systems are not available, as it requires each pair of traffic lines to be equipped with their own emitter-photodetector sensors to ensure continuous automatic operation of the agricultural wide span vehicle.

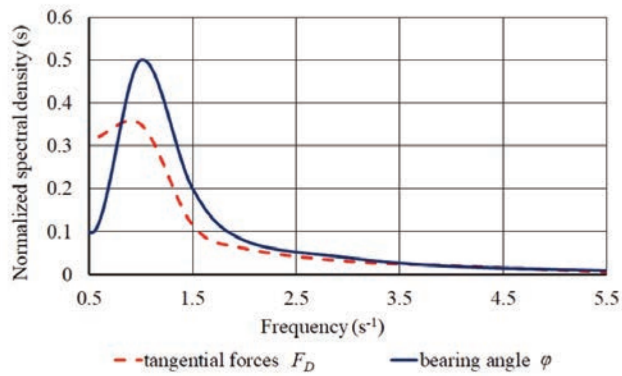

Figure 7. Normalized spectral densities of the fluctuations related to the tangential forces F_{Di} acting on the wheels of one side of the skid steering wide span tractor and its bearing angle ϕ.

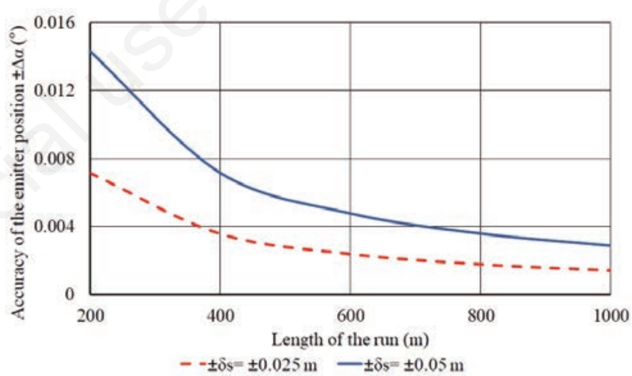

Figure 8. Position accuracy of the emitter ±Δα *versus* the length of the run S at different preset accuracies of the laser beam from the emitter ±δ_s.

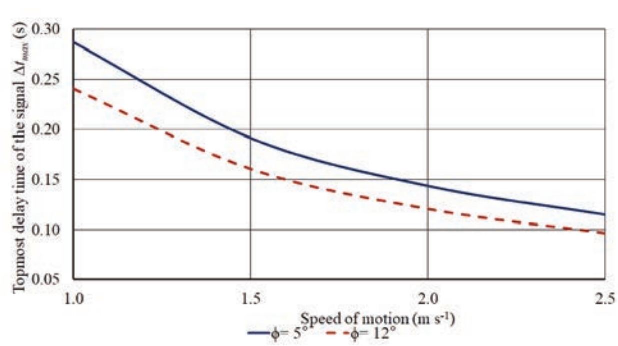

Figure 9. Topmost possible delay time $\Delta_t max$ of the control signal *versus* the speed of the motion of the agricultural wide span vehicle V for different amplitudes of its trajectory deviation.

References

Abe M. 2015. Vehicle handling dynamics. 2nd ed. Elsevier Ltd., Oxford, UK.

Bakker T., Van A.K., Bontsema J. 2011. Autonomous navigation using a robot platform in a sugar beet field. Biosyst. Eng. 109:357-68.

Bulgakov V., Pascuzzi S., Adamchuk V., Ivanovs S., Pylypaka S. 2019a. A theoretical study of the limit path of the movement of a layer of soil along the plough mouldboard. Soil Tillage Res. 195:104406.

Bulgakov V., Pascuzzi S., Adamchuk V., Kuvachov V., Nozdrovicky L. 2019b. Theoretical study of transverse offsets of wide span tractor working implements and their influence on damage to row crops. Agriculture (Switzerland), 9:144.

Bulgakov V., Pascuzzi S., Anifantis A.S., Santoro F. 2019c. Oscillations analysis of front-mounted beet topper machine for biomass harvesting. Energies. 12:2774.

Bulgakov V., Pascuzzi S., Ivanovs S., Nadykto V., Nowak, J. 2020. Kinematic discrepancy between driving wheels evaluated for a modular traction device. Biosyst. Eng. 196:88-96.

Bulgakov V., Pascuzzi S., Nadykto V., Ivanovs, S. 2018. A mathematical model of the plane-parallel movement of an asymmetric machine-and-tractor aggregate. Agriculture (Switzerland), 8:151.

Chamen W.C.T. 1992. Assessment of a wide span vehicle (Gantry), and soil and cereal crop responses to its use in a zero traffic regime. Soil Tillage Res. 24:359-80.

Chebrolu N., Lottes P., Schaefe A., Winterhalter W., Burgard W., Stachniss C. 2017. Agricultural robot dataset for plant classification, localization and mapping on sugar beet fields. Int. J. Rob. Res. 36:1045-52.

Griepentrog H.W. 2009. Safe and reliable: Further development of a field robot. Prec. Agric. 9:857-66.

Hamza M.A., Anderson W.K. 2005. Soil compaction in cropping systems - a review of the nature, causes and possible solutions. Soil Tillage Res. 82:121-45.

He B., Liu G., Ji Y. 2011. Auto recognition of navigation path for harvest robot based on machine vision. Computer Comput. Technol. Agric. 4:138-48.

ISO, 2008. Agricultural tractors - Requirements for steering. Norm ISO 10998:2008. International for Standardization Publ., Geneva, Switzerland.

Yang L., Luo T., Cheng X., Li J., Song Y. 2015. Universal autopilot system of tractor based on Raspberry Pi. Trans. Chinese Soc. Agricult. Engine. 31:109-15.

Ji C., Zhou J. 2014. Current situation of navigation technologies for agricultural machinery. Trans. Chinese Soc. Agricult. Engine. 45:44-54.

Keller T., Sandin M., Colombi T., Horn R, Or D. 2019. Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. Soil Tillage Res. 194:104293.

Luo X., Zhang Z., Zhao Z., Chen B., Hu L., Wu X. 2009. Design of DGPS navigation control system for Dongfanghong X-804 tractor. Trans. Chinese Soc. Agricult. Engine. 25:139-45.

Onal I. 2012. Controlled traffic farming and wide span tractors. J. Agricult. Machine. Sci. 8:353-64.

Park K., 2018. Fundamentals of probability and stochastic processes with applications to communications. Springer, Berlin, Germany.

Raper R.L. 2005. Agricultural traffic impacts on soil. J. Terramechan. 42:259-80.

Wong J.Y. 2001. Theory of ground vehicle. 3rd ed. J. Wiley & Sons, New York, NY, USA.

Zhu Q., Gao G., Niu W. 2016. The automatic navigation driving system of agricultural machinery. Modern Agric. 5:5-67.