On the possibility of controlling the depth of tillage using an inertial navigation system (INS)

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Abstract. The article discusses a number of theoretical aspects of the problem of continuous monitoring of the depth of soil cultivation by agricultural machine and tractor units. A method for controlling the depth of tillage is proposed, based on determining the relative position of the tractor and implement relative to each other and relative to the soil surface. Using the modeling method, the initial requirements for measurement accuracy were obtained and the possibility of using inertial navigation systems for the task at hand was substantiated.

1 Introduction

The quality of agricultural operations related to soil cultivation can be judged by a number of indicators, among which one of the most important is the depth of cultivation, or rather its compliance with agrotechnical requirements for the cultivated crop [1-4]. To adjust and maintain the required depth of working bodies into the soil, trailed agricultural implements usually use the high-altitude method. With this method, during operation, the working parts of the agricultural machine are immersed in the soil under the influence of gravity of the implement itself. Height-adjustable wheels that rest on the soil surface and do not allow the working bodies to descend to a depth exceeding the required values ensure limitation of the immersion depth. The disadvantage of this method of regulation is that in some cases, during the interaction of the working bodies and the soil, forces arise that push the tool to the surface, which leads to a decrease in the set working depth.

The hydraulic mounted aggregation system, invented in 1920 by Harry Fergusson, made it possible to combine a tractor and an agricultural implement into a single machine-tractor unit and significantly increase the efficiency of mechanized tillage [5]. Such systems make it possible to automatically adjust the depth of travel of the working bodies depending on the resistance provided by the soil (force regulation), or depending on the established relative position of the tractor and agricultural implement (position regulation). The force control method is based on the fact that during operation, any deviation in the depth of travel of the working parts causes a change in the resistance exerted by the implement on the tractor hitch, while the hydraulic regulator has a reverse effect on the hitch mechanism and raises (or deepens) the implement to the set values. Positional control implies either one-way locking, which limits the lowering of the implement, but does not interfere with its

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raising when hitting an obstacle, or two-way fixation, which limits both the raising and lowering of the implement.

Systems for automatic control of the stroke depth of working bodies are constantly being improved, allowing the use of both force and position control simultaneously (this method is called mixed control), as well as combining them with the high-altitude method [6-7]. In turn, this makes it possible to reduce the uneven impact of the implement on the tractor, increase the reliability and speed of the unit, and also significantly reduce fuel costs. However, when working on difficult soils, in fields with uneven terrain, the depth of cultivation may differ from the necessary one [8-9].

The most accessible, common and reliable way to assess the depth of tillage is the manual method using depth gauges and metal rulers. This method can be used to set up the implement before work, as well as to control the quality of the tillage operation. However, since the time and place of operation of the actuators of systems for automatic control of the depth of travel of the working bodies is unknown to an external observer and is random in nature, the use of this method to identify areas of the field whose processing depth differs from the required one seems unlikely. One of the directions to solve the problem of continuous monitoring of the depth of tillage is the development of various sensors that make it possible to determine the height of the implement above the soil surface and thus calculate the immersion depth of the working parts. Such sensors are either a mechanical structure that provides measurement of changes in the relative location of the sensitive element (usually a free-rolling wheel) copying the surface of the field and the frame of the implement, or non-contact (ultrasonic, optical, etc.) sensors that directly measure the distance from the installation site to the field surface [10, 11]. A common disadvantage of such systems is the inability to take into account natural unevenness of the field surface, the size of which often exceeds the permissible deviation in the depth of travel of the working bodies ± 10 mm. The use of mechanical systems in production conditions, in addition, requires solving a number of problems associated with mounting the sensor on a tool and its subsequent operation.

As one of the possible solutions to the problem, it would be possible to consider monitoring the parameters of the working fluid in the hydraulic system of the tractor attachment. By ensuring that the values of the measured parameters are linked to geographical coordinates, it would be possible to fix the areas of the field where the system for automatic adjustment of the depth of travel of the working bodies was triggered, and then carry out the necessary measurements in these areas and evaluate both the quality of tillage and the ability of the system to perform its functions. But it should be understood that to implement this approach, firstly, a sufficiently deep knowledge of the design and principle of operation of the hydraulic system of a tractor of this model is required, and secondly, possible interference with the design of the hydraulic system may entail serious risks related to the safety of the researcher and operator, since the pressure of hydraulic oil in the system during operation it reaches very high values [12, 13]. Therefore, the widespread use of this approach for the average user is also not acceptable enough.

During the research process, the authors came to the conclusion that the most accessible parameter for monitoring the depth of tillage will be tracking and measuring changes in the relative position of the tractor and implement relative to each other.

The goal of the authors of this article was to study a number of issues that arise when developing a system that allows monitoring the depth of tillage with mounted agricultural implements.

2 Materials and methods

To achieve this goal, practical experience was studied and an analysis was carried out of existing technical and methodological solutions aimed at both ensuring the required depth of tillage and the possibility of its control. The promising directions for solving the problem, formed as a result of the analysis, were verified by mathematical modeling of the process in the range of the most frequently encountered conditions.

3 Results

Despite the long history of development and improvement, the kinematic diagram of the rear linkage of all agricultural tractors corresponds to the diagram [14] presented in Figure 1. The main dimensions of the linkages are also standardized (Figure 2). The diagram shows that by measuring the deviation from the horizontal of the tractor frame and any of the lower links 2, it becomes possible to determine the change in height 14, which will characterize the depth of immersion of the working parts of the tillage machine into the soil.

Assuming as an initial condition that the permissible deviation in the depth of travel of the working bodies, according to agronomic requirements, should not exceed 10 mm, it follows that it should be measured with at least tenfold accuracy, i.e. no more than ± 1 мм. In a normalized coordinate system (one in which the horizontal angle of inclination in the direction of movement of the tractor relative to the surface is zero), the depth of immersion of the working parts of the implement into the soil x, mm will be determined as the difference between the distance x_2, mm и x_1, mm (Figure 3), where x_2 and x_1 are the vertical projection of the distance from the axis of rotation of the lower links of the hitch (6 on Figure 1) to the axis of the implement's suspension (9 on Figure 1) when the working bodies are buried and when they are on the soil surface, respectively.

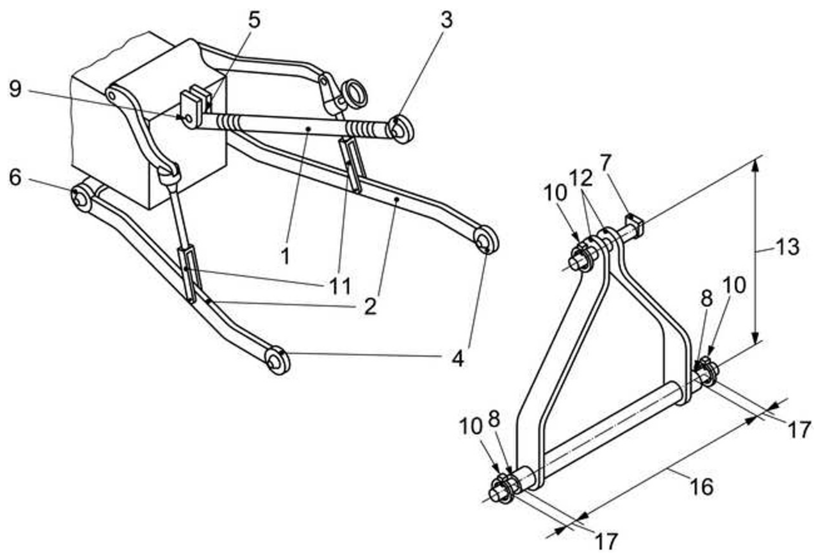

Fig. 1. Components of rear-mounted three-point linkage of an agricultural tractor. (Key: 1 – upper link; 2 – lower link; 3 – upper hitch point; 4 – lower hitch point; 5 – upper link point; 6 – lower link point; 7 – upper hitch attachment; 8 – lower hitch attachment; 9 – upper link attachment; 10 – linchpin; 11 – lift rods; 12 – mast; 13 – mast height; 16 – lower hitch point span; 17 – linchpin hole distance).

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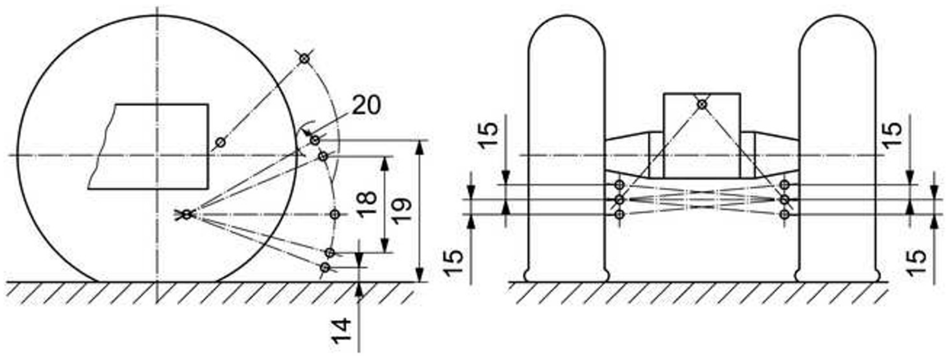

Fig. 2. Dimensions of rear-mounted three-point linkage of an agricultural tractor. (Key: 14 – lower hitch point height; 15 – levelling adjustment; 18 – movement range; 19 – transport height; 20 – lower hitch point clearance.)

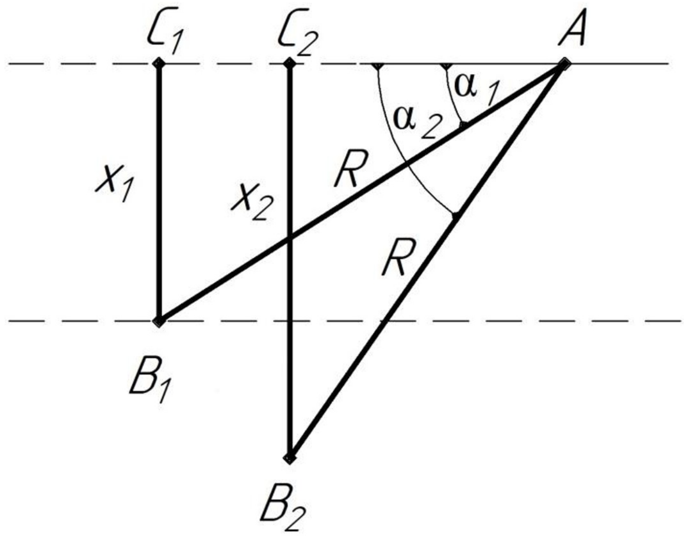

Fig. 3. Scheme for determining the depth of the position of the working bodies of the soil-cultivating implement.

Thus, the position of the working bodies relative to the soil surface will be determined as:

$$x = f(R, \alpha_1, \alpha_2) \tag{1}$$

R – radius of rotation of the implement suspension axis (9 on Figure 1) around the axis of rotation of the lower links of the attachment (6 on Figure 1), mm; α_1, α_2 – angles of inclination of the lower links of the tractor attachment relative to the tractor (relative to the field surface in a normalized coordinate system), rad.

The accuracy of measuring the tillage depth Δx, mm will depend on four arguments and be determined:

$$\Delta x = f(R, \alpha, \Delta R, \Delta\alpha) = \sqrt{(\sin(\alpha) \cdot \Delta R)^2 + (R \cdot \cos(\alpha) \cdot \Delta\alpha)^2} \tag{2}$$

R – mathematical expectation of the radius of rotation of the implement suspension axis (9 on Figure 1) around the axis of rotation of the lower links of the attachment (6 on Figure 1), mm; $\alpha = \alpha_2 - \alpha_1$ – mathematical expectation of the angles of inclination of the lower links of the tractor attachment relative to the tractor (relative to the field surface in the given coordinate system) for immersing the working bodies in the soil to a depth of x, rad.; $\Delta R, \Delta\alpha$ – accuracy of measurement of the corresponding parameters, mm, rad.

By solving equation (2) for any variable, you can obtain its value for the required accuracy Δx:

$$\Delta\alpha = \pm\frac{\sqrt{\Delta x + \Delta R \cdot \sin(\alpha)} \cdot \sqrt{\Delta x - \Delta R \cdot \sin(\alpha)}}{R \cdot \cos(\alpha)}$$

$$if \neg\left(\frac{\alpha - \frac{\pi}{2}}{\pi} \in Z\right) \wedge R \neq 0 \qquad (3)$$

Since the determination of x is the result of two independent measurements, to ensure an accuracy of ±1 mm, the minimum accuracy of Δx should not exceed $\frac{1}{\sqrt{2}}$ mm. To ensure a depth range of working bodies of 0...300 mm using attachments of agricultural tractors with the most probable range $R \in [500; 1500]$ mm, the mathematical expectation α will be in the range 0…0.52 rad. Diagrams of numerical values of measurement accuracy $\Delta\alpha$, which is necessary to determine the depth of tillage in the specified range of expected angular and linear parameters of the work of the mounted device in accordance with the task, are presented in Figure 4.

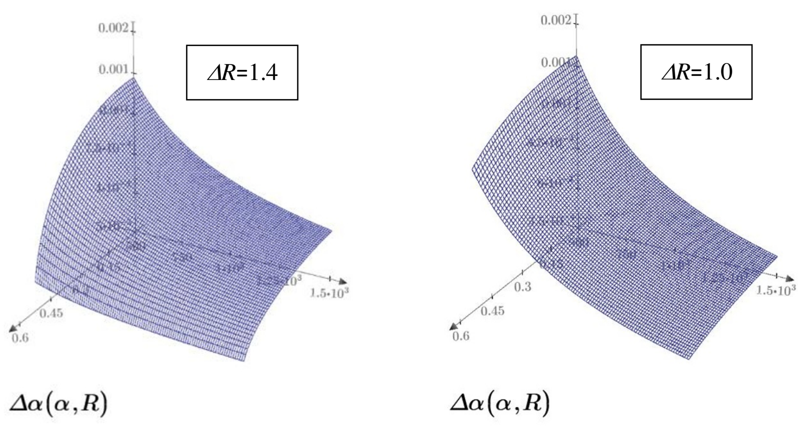

Fig. 4. Required accuracy of measurement of α values, rad.

The diagrams show that the greater the angle of inclination of the lower links of the tractor hitch relative to the tractor (relative to the field surface in the given coordinate system), the more significant contribution to the resulting accuracy is made by the accuracy with which R is measured (with an acceptable measurement accuracy of ± 1,4 mm, the recommended value should not be less than ± 1,0 mm). With an increase in the radius of rotation of the implement suspension axis (9 on Figure 1) around the axis of rotation of the lower links of the hitch (6 on Figure 1), on the contrary, the accuracy of angle measurement is of greater importance, which at the extreme limits of the range should be at leaste $3{,}865 \cdot 10^{-4}$ rad, which is 0°13’17’’.

4 Discussion

The boundary values of the required measurement accuracy obtained as a result of modeling seem quite achievable. In addition, in addition to direct measurements of the radius of rotation of the implement’s suspension axis around the axis of rotation of the lower links of the mounted device, these values can be obtained by calculation using a calibration procedure, in which the depth of immersion of the working parts into the soil is directly measured. On the one hand, under certain conditions, such an approach may turn out to be technically more accessible and adaptive, but on the other hand, it requires additional assessment of the uncertainty of measurement results. In any case, depending on the situation, it is possible to consider both methods and choose the most effective one.

To determine the relative position of the tractor and the implement in space and measure angular values, it is possible to use sensors based on an inertial navigation system (INS), which make it possible to determine the angle of the body’s position in space in a non-contact manner. The advantage of an ANN is that the controlled object is not limited in movement, by a specific environment or location. To determine the position of an object in space, a system used in aviation and known as “heading, pitch, roll” is used. It is able to provide a complete measurement of orientation relative to gravity and the Earth's magnetic field (Figure 5) [15].

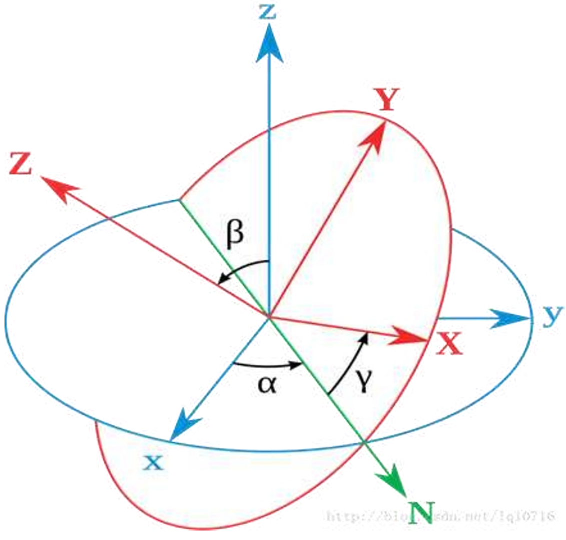

Fig. 5. Euler angles in space.

The required accuracy in determining angular values obtained as a result of modeling can also be ensured. At the same time, installing three INS on the unit (one on the tractor frame, the second on the lower link of the hitch, and the third on the implement frame) will allow real-time monitoring of both the relative position of the tractor and implement with each other, and relative to the soil surface, taking into account directions of movement, longitudinal and transverse slopes, and the integration of such a measuring system into the system for monitoring the operating parameters of a machine-tractor unit will provide the opportunity for a more in-depth analysis and interpretation of the obtained measurement results [16-17].

5 Conclusion

The results of the study show that for continuous monitoring of the depth of soil cultivation with mounted tillage machines, as well as for monitoring the effectiveness of automatic power and position control systems of three-point hitches on agricultural tractors, the method of measuring the relative position of the tractor and implement using inertial sensors has high potential. Being technically accessible, this method will provide the necessary practical measurement accuracy, and the non-contact measurement capabilities provided by inertial navigation systems provide ample opportunities for scaling and integration into various measurement systems using standard interfaces.

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