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Justification of the Software Kinematic Parameters of a Horticultural Autonomous Robotic Platform

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ABSTRACT

The article discusses the issues related to the development and creation of a multifunctional horticultural robotic platform. The necessity of developing a robotic platform best suited to the soil and climatic conditions of the Republic of Armenia is substantiated. A multifunctional robotic platform has been proposed and developed for the cultivation of vineyards and orchards. It is designed for inter-row and inter-vine (inter-trunk) soil cultivation, weed mowing and shredding, fertilization, pest and disease detection, assessment, and chemical control. The platform is equipped with four independently controlled wheels. Kinematic and force analysis of the running gear of the developed robotic platform has been conducted. As a result of these analyses, expressions have been derived that will serve as the foundation for programming the electronic-computer control system of the platform's running gear. These expressions will be used to control the torque movement and angular velocity of all the driving wheels, as well as the rotation of the wheel axes during turning. This approach enables the creation of a robotic platform›s running gear that ensures high mobility, adherence to the designated route, and prevents wheel slippage and skidding during turns. This aspect is particularly important for ensuring the reliability and longevity of the machine, as well as minimizing the damage caused to the cultivated soil by the wheels.

Introduction

The current trends of agricultural development, both globally and in the Republic of Armenia, are determined by the following key factors: the need for increased production of foodstuffs driven by the sharp growth in population, the limited availability of arable lands worldwide, and the necessity to mitigate the irreversible environmental damage caused by the intensification of traditional agrarian production.

It is evident that under the conditions shaped by emerging challenges and demands, the primary direction for agricultural development is the enhancement of efficiency through the digitalization, automation, and robotization of production processes. Initial steps in this direction were taken at the end of the last century, and these approaches have become widely adopted in the current phase.

Advancements in mechanical design, sensor technologies, electronics, and algorithms in the fields of planning and management offer extensive opportunities to perform a wide range of field activities using autonomous robotic platforms (Zagazezheva, Berbekova, 2021; Skvortsov, et al., 2018; Bak and Jakobsen, 2004; Abrosimov and Raykov, 2022).

Robotic platforms possess undeniable advantages, which account for their rapidly increasing demand. These advantages primarily include sensitivity to field-specific conditions, precise operation without operator intervention, low metal consumption, minimal environmental impact, and the ability to perform technological processes over extended periods at relatively low speeds. Ultimately, these features ensure high productivity and efficiency (Akimov, 2017; Cho, et al.; 2002, Tillett, 1991; Abrosimov and Raykov, 2022).

The development of reliable robotic platforms capable of operating for extended periods with minimal human intervention under the changing conditions of cultivated fields is a critical and urgent issue at the current stage (Godin, et al.; 2020; Bak and Hans Jakobsen, 2004; Tillett, 1991).

Although robotic technology began to be introduced into agriculture 25–30 years ago, its widespread and large-scale application gained momentum only in the past decade. According to the International Federation of Robotics, between 2015 and 2020, the global production and deployment of robotics for agricultural purposes increased 30-fold compared to the entire preceding period (www.ifr.org/worldrobotics/, www.rossaprimavera.ru).

Current trends in the development and adoption of robotics indicate that by 2026, the scale of its deployment will increase approximately 20 times compared to 2020, with the market capacity projected to reach $16.6 billion USD (www.rossaprimavera.ru, www.bloomberg.com).

It is worth mentioning that the United States and European Union countries account for the largest share of these volumes, while the development, production, and implementation of robotics in the CIS region are comparatively lower (Abrosimov and Raykov, 2022).

According to leading international developers and manufacturers, robotics used in crop production is categorized into five main groups (Abrosimov and Raykov, 2022; Blasco, et al., 2002):

- soil cultivation (sampling, plowing, cultivation);
- sowing, seedling, rootstock planting;
- crop care (weeding, irrigation, spraying, introduction of fertilizers and herbicides, special care for vineyards and orchards, as well as nurseries);
- assessment and monitoring of parameters such as maturity stage, waste, physical damage, bacterial infection, and other characteristics of agricultural products including size, shape, and quality;
- harvesting (gathering, sorting, distribution, processing, and recycling).

From the perspective of the discussed issue, according to international classification (Abrosimov and Raykov, 2022), small autonomous agricultural robots used in crop production, weighing no more than one ton, are of particular interest. These robots are equipped with remote or semi-automatic control systems, and are outfitted with positioning systems that ensure centimeter-level accuracy. They also feature the ability to attach various implements that perform different functions for different crops.

The technical and software requirements for agricultural robots include marginal dimension and weight specifications, movement speed, accuracy of agrotechnological operations, communication mode and ease of interaction with the operator, the technical vision system, the ability to attach suspended technological iinstallations, and the capability to overcome potential obstacles in the field.

The operational requirements for agricultural robots include reliability, passability, adaptability to various working conditions, type of drive system, energy efficiency, the ability to adjust routes through software under different field conditions, and minimal environmental impact (Abrosimov and Raykov, 2022; www.dijital.gov.ru).

In summary, the characteristics of prospective small agricultural robots, which are expected to have high market demand, must meet the following requirements (Abrosimov and Raykov, 2022; Blasco et al., 2002; Cho et al., 2002):

- a working resource of at least 5–6 hours, with a reliable electric motor and battery;
- it must be equipped with a vision system that works in complex geophysical and natural conditions, including the ability to navigate rough terrain;
- the ability to form and adjust the route with or without the operator's assistance;

- wireless communication with the operator, and the ability to operate autonomously in case of signal loss;
- capability to recognize and solve situational and coordination issues in the field;
- the ability to attach various suspended tools and facilities;
- ease of maintenance and repair, with minimal requirements for tools and specialists.

Though agricultural robots are being widely adopted in the agri-food systems of many countries, their utilization in the Republic of Armenia remains relatively low. The primary reason for this is the high market price of agricultural robots. Additionally, it is important to note that these robots are often designed and developed for other soil and climatic conditions. As mentioned earlier, this factor is critically important for the effective operation of agricultural robots.

One of the solutions to the problem raised in the current situation is the development of a cost-effective, multifunctional robotic platform that is optimally adapted to the soil and climatic conditions of the republic. Based on studies, analyses, and comparative evaluations, a four-wheel robotic platform with all-wheel steered was selected. This design minimizes lateral slippage, which, in turn, reduces wear on the running gear and decreases damage to the soil being cultivated (Bak and Jakobsen, 2004; Torii, 2000).

An objective is set up to develop a robotic platform designed to perform tasks such as soil cultivation in the inter-row spaces of orchards and vineyards, mowing or removing weeds, and carrying out chemical treatments (spraying) to combat pests and diseases.

It has been confirmed that four-wheel robotic platforms with independently controlled wheels are the most suitable for performing the specified agrotechnical tasks in row crops. These platforms excel at maintaining a fixed direction of movement relative to the rows (Toda, et al., 1999; Orebäck and Christensen, 2003).

The recommended robotic platform is designed with three main components: a control system (or station), the robotic platform itself, and tools and devices for performing agrotechnological processes. Communication between the platform and the control system is wireless, allowing a single control system (station) to simultaneously manage multiple robotic platforms within the same field.

The current study focuses on the investigation of the robotic platform's driving train system, as mobility serves as the foundation for all other functional technical and technological characteristics.

Materials and methods

The conceptual diagram of the robotic platform under development is shown in Figure 1. It consists of the platform frame (1), four driving wheels (2), autonomous wheel drive units (3), and wheel steering units (4).

The drive units (3) ensure the movement of the robotic platform and include an electric motor, a gear transmission case (reducer), and a microelectronic control block for the motor. The steering of the wheels is accomplished through a separate steering module (4), which includes a steering electric motor and its electronic control module. The wheel steering unit is positioned above the wheel shaft to create a mechanism with two degrees of freedom.

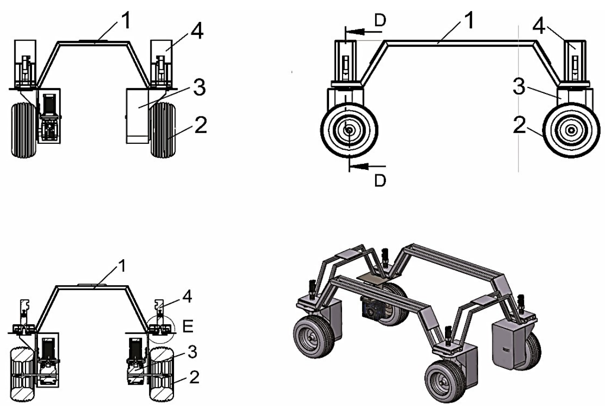

Figure 1. The conceptual diagram of the recommended robotic platform's running system *(composed by the authors)*.

The electronic-computer control unit manages the wheel steering (the rotation of the axles) around the vertical axis based on a software algorithm for the kinematic relationship of the steering angles. It also controls the torque (or current) of the four driving wheel electric motors. The electronics of the steering servomechanism provide feedback/reverse power link/ based on the steering rotation angle. This is a fundamental principle of the agrirobot's structural conceptual design (Bak and Jakobsen, 2004; Toda, et al., 1999; Torii, 2000).

As previously mentioned, the first step in the development and creation of the agrirobot is to identify the relationship and values of the kinematic parameters for stable movement and steering, under which lateral wheel slippage, a highly undesirable phenomenon, must be eliminated.

The movement of an agrirobot in the field (in orchards or vineyards) during the implementation of agrotechnological processes can be categorized into two types: linear movement within inter-row spaces, which involves a flat, parallel motion of the robot platform, and torque movement at the ends of the rows.

Regarding the flat parallel movement of the robot platform, it is executed and maintained in a stable condition through the software management and synchronization of the same rotational torque and angular velocity on all four independently driven wheels. Notably, if one or more wheels deviate from the designated path due to an obstacle, the software must restore the robot platform to its predefined trajectory after overcoming the obstacle. In other words, no turn should occur without an explicit command from the wheel rotation control system.

As for the torque movement of the robot platform, it is of particular interest in the context of the discussed problem. In general, various schemes are employed for the turning of wheeled vehicles. Each scheme features a unique turning kinematics, primarily determined by the position of the instantaneous center of rotation (ICR).

The closer the ICR (Instantaneous Center of Rotation) is to the vehicle's longitudinal axis, the smaller the turning radius, thereby enhancing the platform's maneuverability. From this perspective, preference should be given to a scheme where all wheels are steerable. The closer the ICR (Instantaneous Center of Rotation) is to the vehicle's longitudinal axis, the smaller the turning radius, thereby enhancing the platform's maneuverability. From this perspective, preference should be given to a scheme where all wheels are steerable.

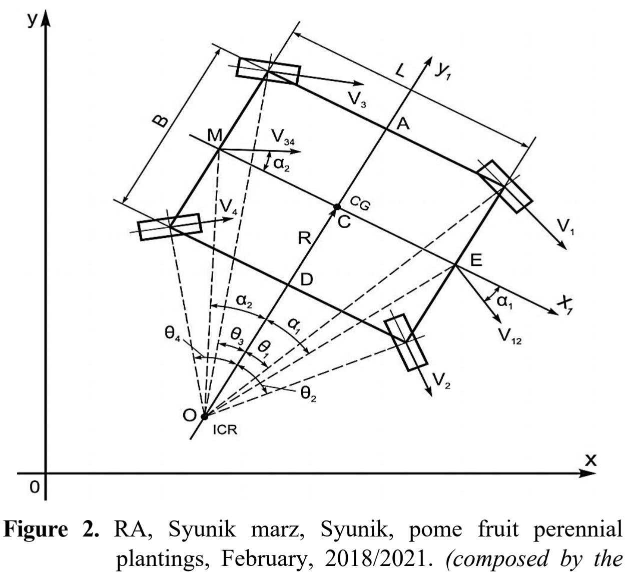

Figure 2. RA, Syunik marz, Syunik, pome fruit perennial plantings, February, 2018/2021. *(composed by the authors)*.

The kinematic scheme of the robot platform with all-wheel turning control is presented in Figure 2.

Existing agricultural robots feature systems controlled by various steering mechanisms, which partially define their areas of application, as well as their degrees of mobility, flexibility, and maneuverability. The proposed design of the autonomous robotic framework allows for the implementation of all existing steering mechanisms, as all four wheels are independent and controlled. Additionally, each wheel can rotate up to a 90-degree angle. These characteristics provide optimal conditions for addressing issues related to the tracking and trajectory programming of the agricultural robot's path, offering a broad scope for the development of efficient algorithms within software control, unconstrained by structural solutions. Another important aspect is the design of the wheel suspension system, which enhances the vehicle's stability and allows it to be tested under varying dynamic loading conditions and speeds. The design and structural solutions extend beyond these elements, providing a broad research field for comprehensive and effective testing.

Results and discussions

When conducting a kinematic analysis of the robot platform's turning, it is important to specify the type of tires based on their stiffness. In the case of flexible tires, the side slip of the wheels must be taken into account, as it significantly affects the angular parameters. Since the robot platform is designed to use tires of a rigid class, this side slip can be neglected, and it can be assumed that the wheels roll without slipping during the turn.

Based on the objectives of the discussed issue, it is important to establish a connection between the turning angles *(θ)* of the wheels.

Let us assume that the turning angles of the front wheels are (θ_1) and (θ_2), with an average turning angle of α_1, similarly, the turning angles of the rear wheels are (θ_3) and (θ_4), with an average angle of α_2. The lateral velocity of the front section is V_{12}, and that of the rear section is V_{34}. If we consider θ_1, θ_2 and α_1 to be positive for the front section, then for the rear section, they are considered negative. According to the scheme represented in Figure, for the front wheels we have:

$$ctg\theta_1 = \frac{R + 0.5B}{0.5L}; \quad ctg\theta_2 = \frac{R - 0.5B}{0.5L}, \qquad (1)$$

or

$$ctg\theta_1 - ctg\theta_2 = \frac{2B}{L}, \quad (2)$$

For the rear wheels, considering that during the turn they rotate in the opposite direction around the vertical/longitudinal axis, the relationship between θ_3 and θ_4 will be:

$$ctg\theta_3 - ctg\theta_4 = \frac{2B}{L}, \quad (3)$$

The boundary values of θ_1 and θ_2 (θ_3 or θ_4) are determined by expression (1). In the case of linear motion $\theta_1=\theta_2=0$, and when $R=-0.5B$, $\theta_1 = \frac{\pi}{2}$; when $R=0.5B$, $\theta_2 = \frac{\pi}{2}$.

Considering that the midpoint (E) of the robot platform's front section moves with a velocity at an angle relative to the X_1 axis (Fig. 2), and the corresponding point M of the rear section moves with a velocity V_2 at an angle of a_2, the radius of curvature for the turn, based on the scheme will be:

$$R = \frac{L}{tg\alpha_1 + tg\alpha_2}. \quad (4)$$

Since the version with rigid wheels is being considered, we can practically assume that $\alpha_1=\alpha_2=\alpha$, in that case:

$$\mathrm{R} = \frac{L}{2tg\alpha}. \quad (5)$$

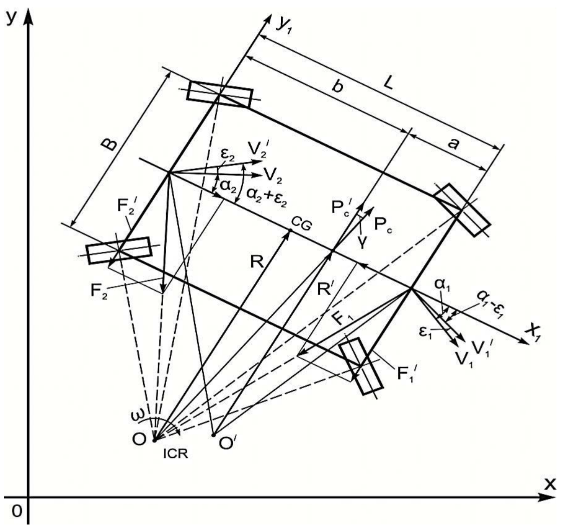

Figure 3. The diagram of forces acting on the robotic platform's drivetrain *(composed by the authors)*.

For a given L, α should take on a boundary value such that $R > \frac{B}{2}$, otherwise, the ICR (Instantaneous Center of Rotation) will fall within the platform's dimensions of BxL, which is undesirable from the perspective of unstable turning. This is also mentioned in other studies dedicated to the analysis of the driving/running mechanisms of robot platforms (Bak and Jakobsen, 2004; Orebäck and Christensen, 2003; Litvinov, 1971).

From the final expression (5), we can determine the turning angle (α) and the angular velocity (ω).

$$\mathrm{tg}\,\alpha = \frac{L}{2R} \text{ and } \omega = \frac{V}{R} = \frac{V \cdot 2tg\alpha}{L}. \quad (6)$$

To assess the stability of the robot-platform's movement, it is necessary to also study the forces acting on the frame during turning. Since turning can occur at relatively higher speeds in the robot-platform's transportation mode, the side slippage of the wheels must be also considered, as a result of which the velocity vectors V_1 *and* V_2 deviate from their initial directions by ε_1 and ε_2, respectively. The diagram in Fig. 3 illustrates the schematic of the forces acting on the robot-platform's running section.

When performing the force analysis, we assume that the driving and resistance forces acting on the wheels are balanced.

In that case, a centrifugal force acts at the center of mass of the platform $\mathrm{P_c} = \frac{mv^2}{R}$, while lateral reaction forces F_1 and F_2 act on the wheels. Assuming that the equivalent lateral reaction forces the wheels are applied at the front and rear points of E and M, let's decompose these forces in the directions of the longitudinal *(x_1)* and transverse *(y_1)* axes. From the diagram (Fig. 3), it follows that:

$$\left.\begin{aligned} F_1' &= P_c'\frac{b}{L} = P_c'\cos\gamma\cdot\frac{b}{L} \approx \frac{mv^2\cdot b}{R'L}, \\ F_2' &= P_c'\frac{a}{L} = \frac{mv^2}{R'}\cdot\frac{a}{L}\cos\gamma\cdot\frac{b}{L} \approx \frac{mv^2}{R'}\cdot\frac{a}{L} \end{aligned}\right\}, \quad (7)$$

where R' is the turning radius accounting for the wheels lateral slippage. From the diagrams (Figure 2 and Figure 3) and (4) expression, it follows that:

$$R' = \frac{L}{tg(\alpha_1 - \varepsilon_1) + tg(\alpha_2 - \varepsilon_2)}, \quad (8)$$

γ is the angle of deviation of the turning radii caused by the lateral slip of the wheels. Since γ is relatively small (not exceeding 50), in practical calculations, we assume $cos\gamma \approx 1$.

Since we have assumed that $\alpha_1=\alpha_2=\alpha$,, we can also write:

$$F_1'=F_1 \cdot cos\alpha \approx K_1\, \varepsilon_1; \;\; F_2'=F_2 \cdot cos\alpha \approx K_2\, \varepsilon_2 \qquad (9)$$

where K_1 and K_2 are the lateral slippage coefficients of the front and rear wheels, respectively.

(7) and (9) expressions indicate that:

$$\frac{mv^2}{R'} \cdot \frac{b}{L} = K_1 \varepsilon_1 \;\; \text{and} \;\; \frac{mv^2}{R'} \cdot \frac{a}{L} = K_2 \varepsilon_2, \qquad (10)$$

wherefrom:

$$\varepsilon_1 = \frac{mv^2}{R'} \cdot \frac{b}{L \cdot K_1} \;\; \text{and} \;\; \varepsilon_2 = \frac{mv^2}{R'} \cdot \frac{a}{L \cdot K_2} \qquad (11)$$

From the last expressions (11) it follows that if the center of the robotic platform mass is located at its geometric center $a = b = \frac{L}{2}$ and all four wheels have the same lateral slippage (deviation) coefficients, then $\varepsilon_1=\varepsilon_2=\varepsilon$. Since it is intended to use rubberized rigid wheels in the design of the robotic platform, which inherently have a small lateral slip angle (ε), compared to the turning angle (α), the expression in (5) can provide sufficient results for practical calculations. For example, if we assume the following values: $L=1.85$ m, $a=b=0.925$ m, $m=600$ kg, $v=1.67$ m/s, $\alpha=45^0$, $R=0.925$ m and $K=1.7 \cdot 10^4$ N/rad (an average value for the mentioned rigid wheels), then according to the expression in (11) the value of will be 0.052 rad, which is much smaller than α=0.785 rad.

From the obtained expression (11), it follows that the turning angle (α) and radius (R *or* R') are related to the robot platform's maneuverability, which depends on the position of the mass center, the lateral slippage coefficient, and the velocity in the turning zone. Moreover, as the speed increases, the turning radius decreases, which increases the turning capacity which in turn can lead to loss of movement stability. However, in the discussed case, there is no such risk, as the speeds do not exceed 5÷10 km/h.

Conclusion

A multifunctional platform for the cultivation of orchards and vineyards has been recommended and developed. It is equipped with four independent, self-steering wheels, ensuring high maneuverability and precise execution of the designated routes and agrotechnological functions.

As a result of the kinematic and force analysis of the robotic platform's drivetrain, expressions have been derived that serve as the basis for programming the control algorithm of the driving wheels' electronic-computer system. This system must ensure high mobility, movement stability, and the elimination of lateral slip (deviation) in all wheels during turns.

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Declarations of interest

The authors declare no conflict of interest concerning the research, authorship, and/or publication of this article.

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