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Study of Geometric Capabilities of Agrarian Robot's Original Model

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Abstract. A mathematical model of an original agrarian robot designed, for example, for automatic control of growth and condition of plant crops in a greenhouse or spraying is presented. The model consists of a transportation robot, a platform with two degrees of mobility and a parallel manipulator with two degrees of mobility. A study on the selection of geometric dimensions that provide access of the manipulator to all parts of the plant, the typical dimensions of which are about 1 meter in height and 0.4m width and depth, is performed. The solution of direct and inverse positional kinematic problems has been obtained and the dependences of the manipulator rotation angles and platform position at rectilinear movements of the working body have been presented

INTRODUCTION

One of the main problems facing humanity today is to increase the world's population and its food supply [1]. A successful solution to this problem is possible through the industrialization of food production of plant origin and the introduction of "smart" farming with the use of robotic complexes that are able to perform a large amount of routine work.

Greenhouse vegetable crops (tomatoes, cucumbers, etc.) are common and useful foodstuffs, they grow easily and mature in a short period of time. A number of important problems arising in industrial greenhouses (untimely harvesting, crop disease, pest infestation) can be identified, which can be solved with the help of agricultural robots. Currently, the solution of these problems is limited by traditional approaches using a large share of human labor. The use of robots in crop production allows to free a person from performing a number of monotonous production operations; reduce the loss of working time associated with human errors [2]. Reviews of agrarian robots are presented in [3-5].

The designs of an agricultural robot and its control system should minimize crop damage during operation, which requires a high degree of automation of mobile robots, manipulators or work units. Another key design challenge is the selection of the set of sensors to be used, which will solve the issue of positioning the robotic system, monitoring the greenhouse environment, etc. Modern trends in the development and design of agrarian robotic systems are associated with increasing flexibility and speed of their operation, with cost reduction, creation of a system of parallel functioning robots for different purposes.

The following types of robotic systems are distinguished according to their functional purpose. Harvesting robots aim to reduce seasonal workload [6], but currently most developments lose out to manual labor in terms of operation speed [7]. Monitoring robots are used to monitor growth, disease, climate, soil (especially in water scarce areas) and have several advantages over stationary systems [3]. Analyzing the collected data allows decisions to be made about the necessary set of works in the greenhouse. Monitoring robots also simplify the work of agronomists when conducting research to optimize cultivation techniques and detect pathologies at early stages. The next type of robots is designed for planting, i.e. transferring seedlings from germination trays to their final planting site in the greenhouse [8]. The last large group of developments is devoted to robotic sprayers, which can significantly reduce

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pesticide application by using information on the condition of each bush [9]. Most relevant is the development of agricultural robots that are much more efficient in their functions compared to manual labor. For example, monitoring robots capable of detecting diseases at early stages with high reliability, or spraying robots capable of spot application of pesticides

The purpose of this paper is to build a mathematical model of the original agricultural robot and investigate its geometric capabilities.

MATHEMATICAL MODEL

We study an original mathematical model of an agrarian robotic complex, which can be used in automating the functions of monitoring plant crops, their spot spraying or harvesting in greenhouse farms. The model is schematically represented in Fig. 1. The complex includes a transportation robot that moves along rows with plant crops, a platform that can move vertically and rotate horizontally, and a parallel manipulator with two degrees of mobility attached to the platform. Chambers, sprayer nozzles or fruit picking mechanisms can be used as a manipulating device.

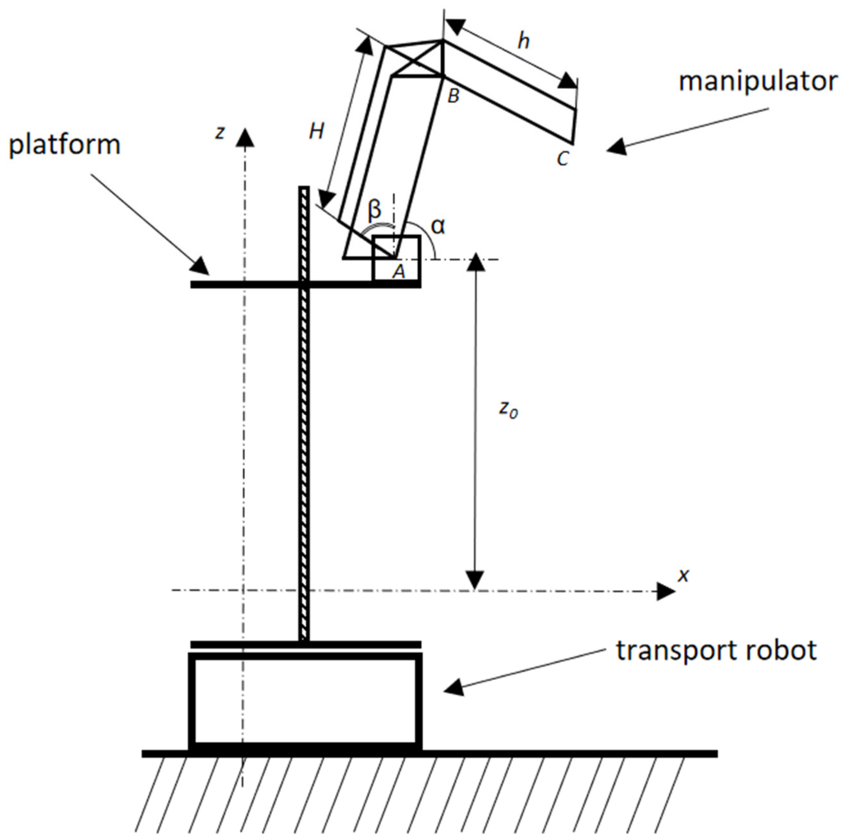

FIGURE 1. Schematic representation of the agrarian robot model

The parallel design of the manipulator allows to place the motors realizing the rotations of the links on its base, which reduces the load on the links and reduces the values of the torques of rotation of the motors to hold and move the load.

The Cartesian coordinate system associated with the transportation robot is used, and the axes are directed according to Fig. 1. The robot actuators set the manipulator link angles α and β, and the height and rotation angle of the platform z_0 and φ, respectively. The position of the working body is defined as follows

$$x = \left(x_0 + H\cos\alpha + h\sin\beta\right)\cos\varphi,$$
$$y = \left(x_0 + H\cos\alpha + h\sin\beta\right)\sin\varphi, \qquad (1)$$
$$z = z_0 + H\sin\alpha - h\cos\beta.$$

In this case, the design of the manipulator imposes restrictions on the angles to avoid crossing the links AB and BC

$$90 - \alpha + \beta > \delta\,. \qquad (2)$$

Consider the case of robot orientation when the manipulator links lie in the xz plane (φ = 0o). Fig. 2 shows the working areas for three variants of lengths AB and DC at $\delta = 15^{\circ}$, x0 = 0.1m, $15^{\circ} \le \alpha \le 165^{\circ}$, $15^{\circ} \le \beta \le 135^{\circ}$, $0 \le z_0 \le 0.5$. Qualitative analysis shows that the third variant provides the reachability by the working body of almost all parts of the crop, the typical dimensions of which are 0.4m in width and 1m in height. The workspace of the robot is generated by rotating the curves presented in Fig. 2 around the z-axis, i.e., by changing the values of the platform rotation angle φ. Thus, there is a possibility of different orientations of the manipulator device with respect to the desired point.

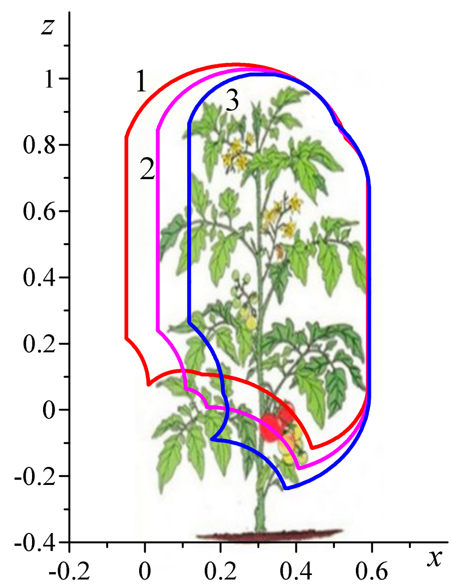

FIGURE 2. Working area of the robot depending on: 1 – H = 0.3m, h = 0.2m; 2 – H = 0.25m, h = 0.25m; 3 – H = 0.2m, h = 0.3m.

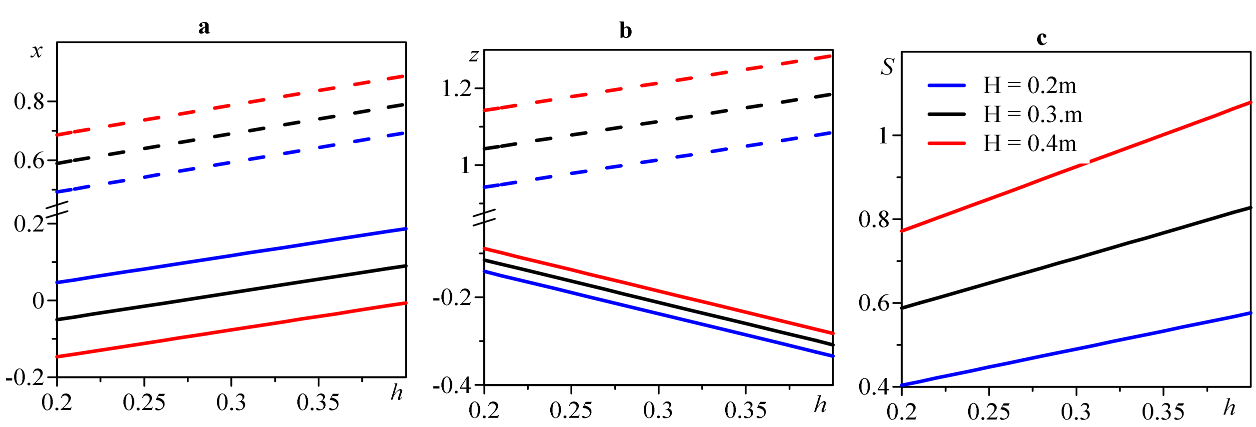

FIGURE 3. Dependence of maximum (dotted line) and minimum (solid line) coordinates x (**a**) and z (**b**) and working area (**c**) as a function of arm length BC at $0 \le z_0 \le 0.6$ and $\varphi = 0^{o}$

The influence of the manipulator link sizes H and h on the value of the maximum and minimum coordinates along the x and z axes, which can be reached by the working body, as well as the working area at a fixed rotation angle φ are shown in Fig.3,4.

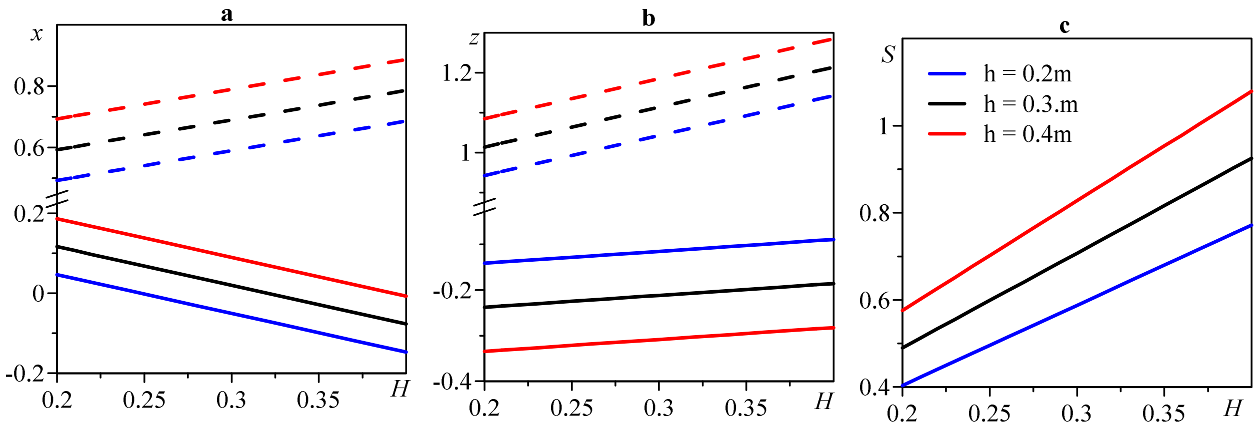

FIGURE 4. Dependence of maximum (dotted line) and minimum (solid line) coordinates x (**a**) and z (**b**) and working area (**c**) as a function of arm length AB at $0 \le z_0 \le 0.6$ and $\varphi = 0^{\circ}$

Increasing the arms AB and BC leads to an increase in the maximum coordinates in the x and z axes. Increasing the length of the BC link increases the working area in the negative direction of the z-axis, allowing the manipulator device to move below the platform, while increasing the AB link reduces the working area in this direction. The working area increases with increasing h or H while fixing the length of the other arm. All investigated characteristics depend linearly on the values of lengths AB and BC.

The solution of the inverse problem, which allows us to determine the manipulator angles α and β to achieve the necessary coordinate x, z by the working body at a fixed platform height z_0 and rotation angle φ=0 (y=0), is as follows:

$$\alpha = \cos^{-1}\left(\frac{a(x-x_0) - sign(z-z_0)\sqrt{a^2(x-x_0)^2 - \left(a^2-(z-z_0)^2\right)\left((x-x_0)^2+(z-z_0)^2\right)}}{(x-x_0)^2+(z-z_0)^2}\right),$$
$$\beta = \cos^{-1}\left(\frac{-b(z-z_0) + \sqrt{b^2(z-z_0)^2 - \left(b^2-(x-x_0)^2\right)\left((x-x_0)^2+(z-z_0)^2\right)}}{(x-x_0)^2+(z-z_0)^2}\right), \tag{3}$$
$$a = \frac{H^2 - h^2 + \left((x-x_0)^2+(z-z_0)^2\right)}{2H},\ b = \frac{H^2 - h^2 + \left((x-x_0)^2-(z-z_0)^2\right)}{2h}$$

The function $sign(z)$ takes the value 1 in the case of a positive argument and -1, conversely, in the case of a negative argument. At the same time, the solution (3) constraints the rotation angles of the links $15^{\circ} \le \alpha \le 165^{\circ}$, $15^{\circ} \le \beta \le 135^{\circ}$ and $\delta = 15°$. The robot design allows moving the platform in the vertical direction by setting the value of z_0, so there is no single link configuration to achieve the required coordinate x, z by the working body. The only solution is selected by minimizing the value of z_0, which provides the minimum height of the center of mass of the platform on which the motors are placed.

Fig. 5 shows the change in the values of angles α, β and platform height z_0 during rectilinear movement of the working body along the horizontal, vertical and inclined trajectory. The values of angles are given in radians, and heights - in meters.

In case the platform rotation angle is considered, the required point x, y, z is achieved at the following values of the angle

$$\varphi = tan^{-1}(\frac{y}{x})$$

In this case, the values of the rotation angles of the links α, β and the platform height z0 are calculated by the formulas (3) considering the replacement of x by $\sqrt{x^2 + y^2}$.

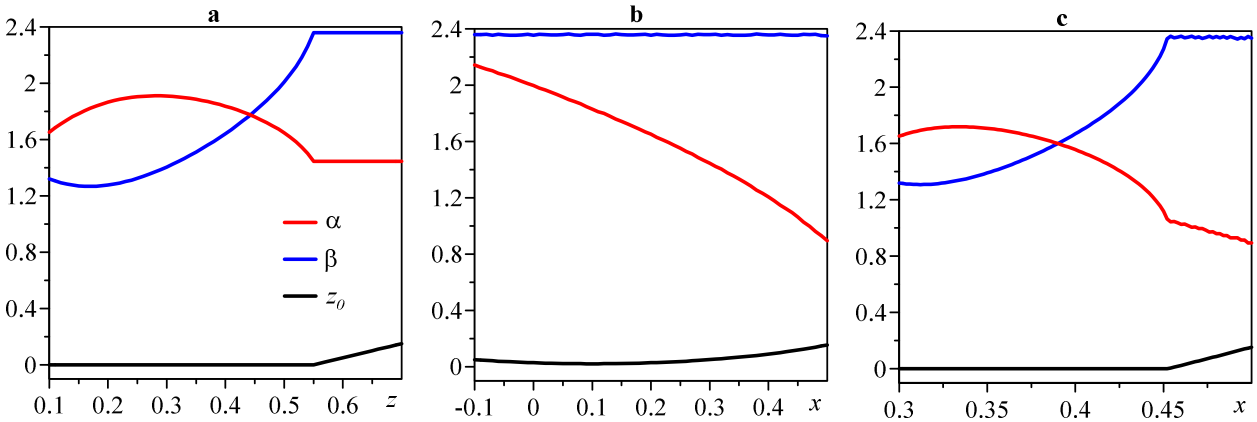

FIGURE 5. Changes in rotation angles α, β and platform height z_0 when the manipulator device moves in a straight line (H = 0.3, h = 0.3, x_0 = 0.1, y = 0): from (0.3, 0.1) to (0.3, 0.7) (**a**), from (-0.1, 0.6) to (0.5, 0.6) (**b**), from (0.3, 0.1) to (0.5, 0.6) (**c**).

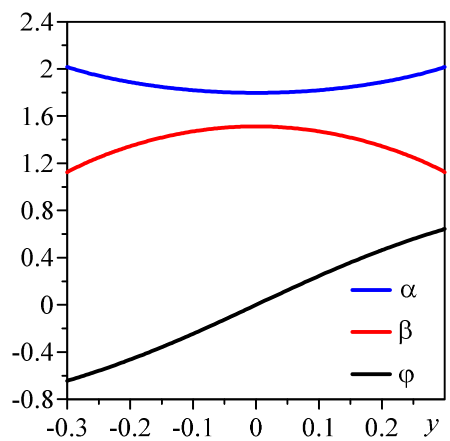

FIGURE 6. Changes in rotation angles α, β and φ due to straight-line movement of the manipulator device

Fig. 6 shows the change of rotation angles of the manipulator and the platform when moving along a rectilinear trajectory parallel to the y-axis. The platform coordinate z0 remains unchanged at such coordinate values.

CONCLUSION

The solutions of forward and inverse kinematic positional problems for the original model of the agricultural robotic complex consisting of a transport robot, a platform and a parallel manipulator are presented. Parametric studies of the working space depending on the geometric dimensions of the manipulator links have been carried out and the optimal values for the working body to reach all parts of the crop with a height of 1m have been determined. Based on the solution of the inverse problem, the dependences of the given coordinates (rotation angles of the manipulator links and platform lifting height) for the realization of rectilinear movements by the working body along horizontal, vertical and inclined trajectories have been constructed.

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