Kinematic study of a robot-weeder with a sprayer function and fertigation

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Abstract. The paper presents the design of a robot-weeder with the function of a sprayer and fertigation for mechanical point-weed destruction and chemical treatment of plants. Based on the kinematic analysis, the optimal geometrical parameters of the constituent parts and components of the structure are obtained, the configurations of the service areas of the cutting tool and the spray nozzle are determined.

1. Introduction

Recently, automation and robot automation of production processes in all industries have been developing at an accelerated pace. One of the most popular and relevant industry today is the agricultural industry, primarily due to the use of labor-intensive heavy operations in the cultivation and care of row crops [1, 2 and 3]. Such operations include inter-row processing [4], which is based on the mechanical or chemical destruction of weeds [5, 6 and 7], using a laser weeding robot [8], as well as chemical treatment from pests and diseases of cultivated plants [9]. Weather conditions and the type of cultivated plants allow inter-row processing several times and as soon as possible [10]. In this case, the mechanical destruction of weeds by the working parts of the cultivator (paw) is possible with continuous cultivation and only between the rows, without affecting the weeds that are in rows between cultivated plants. In addition, the larger the size of the cultivated plant, the greater the likelihood of damage and the increase in the protective zone around the plants is required. Removing weeds in rows requires additional economic costs, and basically this work is done with the help of manual labor. To solve these problems in foreign countries they use robotized machines that allow destroying weeds by mechanical and chemical means, while reducing the volume of herbicides by 2-3 times [11]. One of these countries, manufacturers of robotic machines are Switzerland with the development of agricultural robot (Ecorobotix) (Figure 1) [12], designed for spot thinning and weeding. The agricultural robot (Ecorobotix) has a number of advantages, it is equipped with a computer vision system designed to identify weeds. It sprays the weed with a small dose of herbicide, and is also guided by GPS using touch sensors, uses power from a battery charged by photovoltaic cells mounted on the upper plane. It can work up to 12 hours after recharging and can process about 3 hectares of crops per day.
2. Results and Discussion

Based on studies of manipulation systems for foreign analogues, the authors developed and patented (Figure 2) the design of a mobile weeding robot with a sprayer and fertigation function, intended for mechanical spot removal of weeds in rows, and with the ability to selectively cultivate plants from diseases and pests.

The attached robotic engineer with a sprayer and fertigation function (Figure 2) consists of frame 1 with control wheels, a control and navigation system with instrumentation and power supply system 2, vision sensor 3, which is installed in the front in the lower part of frame 1 for weed detection in row and row spacing, as well as pests and diseased plants.

For the mechanical destruction of weeds, there is a cutting tool of the working part 4, presented in the form of a spiral with knives, which rotates from the DC motor 5 and vertically moves with the help of a linear actuator (actuator) 6. The working part with the drives is arranged vertically one after the other and fixed rigidly on the carriage 7 guide with carriage 8.
Moving in the horizontal plane of the working part 4 is carried out using three linear actuators 6, located in the horizontal plane and are interconnected by means of three guides and a cross member with carriages 7-10.

For chemical treatment of plants from pests and diseases in the rear lower part of frame 1, a tripod manipulator is installed, which is a pyramid, the edges of which are actuating linear actuators 6 and are connected at one point with a spray nozzle 11 by means of an articulated five-mobile node 12. Also in the rear parts frame 1 is attached to the tank with the preparation for the treatment of plants and the pump with the dispenser 13, which are connected to the spray nozzle 11 using a flexible hose.

On the basis of the proposed design, we will conduct a kinematic study of a robber farmer with a sprayer and fertigation function, which will include the following: determination of the optimal geometrical parameters of the component links and structure nodes, determination of the service areas of the cutting tool and the spray nozzle.

The optimal geometrical dimensions of two linear actuators 6 are located at a certain angle in the horizontal plane (Figure 2) and their attachment points to the base are determined from the conditions for the realization of the required movement, the required service area and restrictions imposed by the parameters [13,14]. For most tilled crops, the distance between plants is \( d = 700 \text{ mm} \) and the protection zone \( e = 150 \text{ mm} \) as shown in Figure 3. To obtain the required service area that would cover two rows when designing the construction of an industrial robot, it is necessary to determine the distance \( a \) between attachment points B and C of two linear actuators 6.

Figure 3. The design scheme of two linear drives (top view).

We take the following parameters as the main geometric constraints in the synthesis of a robot-weeder based on a flat mechanism: angle of the sector of coverage in the horizontal plane \( \Theta \geq 90^\circ \) (field plane); maximum departure of executive units \( l_{\text{max}} > |l| \).

The largest sector angle \( \Theta \) is obtained in the case when the length of the actuator \( l_3 \) is minimal, and \( l_2 \) is maximum in the extreme right position, and vice versa \( l_3 \) is maximum and \( l_2 \) is minimal in the extreme left position. Since the mechanism is symmetric about the axis \( Oy \), it is sufficient to consider its movement with a constant minimum length of the actuator \( l_2 \) and a change only \( l_3 \).

Having accepted the above-mentioned assumptions \( (l_2=\text{const}) \), we obtain a planar replacement circuit with swinging actuator \( l_3 \) and rocker \( l_2 \). Then, when going from one extreme \( A_2 \) position to
another, $A_3$, the length of the actuator $l_2$ changes from $l_{2\text{min}}$ to $l_{2\text{max}}$, turning the actuator $l_1$ through the angle $\alpha$. The elongation of the actuator is denoted by $\Delta l = l_{2\text{max}} - l_{2\text{min}}$, the ratio of the length of the stationary actuator to the stroke of the rod is the coefficient of elongation value of the actuator $k = l_2/h$. For electric cylinders (actuators), the range of variation $k = 1.56$ is subsequently taken.

It should be noted that the efficiency of the mechanism and its efficiency largely depend on the pressure angle $\upsilon$, the angle between the axis of the actuator and the velocity vector of the point of application of force. The permissible pressure angle in the lever mechanisms, as a rule, should not exceed $[\upsilon] = 60^\circ$. A rational in terms of dimensions scheme of the mechanism is realized under the condition $[\upsilon] = [\upsilon]$, but on the other hand, the smaller $[\upsilon]$, the less friction loss in hinges.

For the design scheme shown in Fig. 3, we obtain the expression of the vector contour:

\[
(k + 1)^2 \cdot \Delta l^2 - 4l_{3\text{min}}^2 \cdot \sin\left(\frac{\alpha}{2}\right) \cdot (k + 1) \cdot \cos([\upsilon] - \frac{\alpha}{2}) \cdot \Delta l + 4l_{3\text{min}}^2 \cdot \sin^2 \left(\frac{\alpha}{2}\right) - l_{2\text{min}}^2 = 0, \quad (1)
\]

We determine the between-centers distance $a$, mm:

\[
a = \sqrt{l_{2\text{min}}^2 + (l_{3\text{min}} + \Delta l)^2 - 2l_{3\text{min}}(l_{3\text{min}} + \Delta l)\sin([\upsilon])}. \quad (2)
\]

where $l_{2\text{min}} = 700$ mm and $l_{3\text{min}} = 700$ mm – actuator size, $\Delta l = l_{2\text{max}} - l_{2\text{min}} = 450$ mm – actuator rod stroke, substituting in dependence (2) we get $a = 646$ mm.

We find the maximum departure $L_{\text{max}}$ of point $A$ from the edge of the base:

\[
L_{\text{max}} = \sqrt{l_{2\text{max}}^2 - 0.25a^2} = \sqrt{1150^2 - 0.25\times646^2} = 1103.7 \text{ mm}. \quad (3)
\]

The next task of the kinematic analysis of the robot-weeder is to determine the configuration of the service area of the cutting tool, which is the spatial aggregate movement of point $M$ (Fig. 4).

The theoretical zone of possible movements of the point $M$ depends on the ratio of the lengths of the links $l_k, k = 1 \div 4$, which are further taken as generalized coordinates, and on the relative position of the attachment points of the actuators and the frame.

The coordinates of the point $M$ of the cutting working part in the absolute coordinate system $O_{XYZ}$ have the form:

\[
\begin{align*}
X_M &= l_1 + X_A \\
Y_M &= Y_A \\
Z_M &= l_4
\end{align*}
\]

where $X_A$ and $Y_A$ - coordinates of point $A$, actuator stem connections $l_2, l_3$.

The equations of connection between the coordinates of point $A$, the lengths of the links $l_2, l_3$, and the relative position of their attachment points are:

\[
\begin{align*}
l_2^2 &= X_A^2 + (Y_A - Y_B)^2 \\
l_3^2 &= X_A^2 + (Y_A + Y_B)^2
\end{align*}
\]
where $Y_B$ - actuator mounting coordinate $l_2$.

![Image](image_url)

**Figure 4.** Kinematic scheme of the robot for the mechanical removal of weeds.

Thus, the dependences of the coordinates of the point $M (X_M, Y_M, Z_M)$ on the lengths of the links $l_k, k = 1 \div 4$, and the coordinates of the attachment points of the actuators $l_2$ and $l_3$ take the form:

\[
\begin{align*}
X_M &= l_1 + \sqrt{l_2^2 - \left( \frac{l_2^2 - l_3^2}{4Y_B} \right)^2} + \frac{l_2^2 - l_3^2}{2} - Y_B^2 \\
Y_M &= \frac{l_3^2 - l_2^2}{4Y_B} \\
Z_M &= l_4 
\end{align*}
\]  

(6)

The system of equations (6) is a solution of the direct kinematics problem and completely determines the theoretical possible range of displacements of the point $M$ in space, i.e. the working area of service of the cutting working part of the robot-weeder, and also allows one to formulate the conditions excluding its falling into the dead position [15,16].

Restrictions are imposed on the coordinate $Y_B$ of the attachment point of the actuators $l_2$ and $l_3$.

\[
l_2^2 - \left( \frac{l_2^2 - l_3^2}{4Y_B} \right)^2 + \frac{l_2^2 - l_3^2}{2} - Y_B^2 \geq 0
\]  

(7)

\[
Y_B \geq \pm \sqrt{l_2^4 + 2 \cdot l_2^2 \cdot l_3^2 + 4 \cdot l_2^2 + l_3^4 - 4 \cdot l_3^2} + \frac{l_2^2 + l_3^2}{4}
\]  

(8)
Knowing the parameters of the lengths of the actuators \((l_{\text{min}} = 700 \text{ mm}, \ l_{\text{max}} = 1150 \text{ mm})\) and \(a = 646 \text{ mm}\) - the distance between the attachment points of the actuators \(l_2\) and \(l_3\) on the frame, coordinates \(Y_B = Y_C = a/2\), solving the system of equations (6) using the Mathcad software package, we obtain the working area cutting working part of the robot-weeder, (figure 5).

![Figure 5. Working area of the cutting working part of the robot-weeder.](image)

From the shape of the working area of the cutting working part of the robot-weeder in Fig. 4, we can see that the point M moves along the X axis from \(\text{min (X)} = 1321 \text{ mm}\) to \(\text{max (X)} = 2254 \text{ mm}\); Y-axis from \(\text{min (Y)} = -644 \text{ mm}\) to \(\text{max (Y)} = 644 \text{ mm}\); on the Z axis from \(\text{min (Z)} = 700 \text{ mm}\) to \(\text{max (Z)} = 1150 \text{ mm}\).

Chemical treatment of plants in rows of pests and diseases is performed by a spray nozzle, which is supplied by a tripod manipulator. Since the rows are at some distance from each other, it is necessary to determine the spray injector service area, which is the spatial cumulative displacement of the point \(K\) (Figure 6).

The theoretical zone of possible displacements of the point \(K\) depends on the ratio of the lengths of the links \(L_1, L_2, L_3\), which are further taken for generalized coordinates, and on the relative position of their attachment points on the base.

![Figure 6. Kinematic scheme of tripod-injector with nozzle.](image)

To determine the trajectory of movement \(t, K\) was adopted as a coordinate system - absolute \(OXYZ\). To compose the equations of the relationship between the coordinates of the point \(K\), the
length of the links and the relative position of their attachment points, the relationship between the coordinates of two points in space and the distance between them is used:

\[
\begin{align*}
(X_E - X_A)^2 + Y_E^2 + Z_E^2 &= L_1^2, \\
(X_E - X_A)^2 + (Z_E - Z_N)^2 &= L_2^2, \\
(X_E - X_A)^2 + Y_E^2 + Z_E^2 &= L_3^2,
\end{align*}
\]

(9)

where \(X_E, Y_E, Z_E\) - the coordinates of the point \(K\) in the moving coordinate system; \(L_1, L_2, L_3\) - current manipulator link lengths; \(X_A = -X_A', ZN\) - constant, in the selected system, the coordinates of the points of attachment of the links of the manipulator.

Solving the system (9), we obtain the dependencies of the coordinates of a point \(E(X_E, Y_E, Z_E)\) on the lengths of the links \(L_1, L_2, L_3\) and the coordinates of the attachment points of the manipulator base:

\[
\begin{align*}
X_E &= \frac{L_2^2 - L_3^2}{4X_A}, \\
Y_E &= \left(\frac{L_1^2 - L_2^2}{16X_A^2} - \frac{\left(-L_1^2 + 0.5L_2^2 + 0.5L_3^2 - X_A^2 - Z_N^2\right)^2}{4Z_N^2}\right)^{1/2}, \\
Z_E &= \frac{-L_1^2 + 0.5L_2^2 + 0.5L_3^2 - X_A^2 + Z_N^2}{2Z_N}.
\end{align*}
\]

(10)

Knowing the parameters of the length of the actuator \((L_{min} = 600\ mm, L_{max} = 950\ mm)\) and \(a = 524\ mm\) is the distance between the attachment points of the actuator on the base, the coordinates \(X_A = X_B = a/2, Zc = a\sqrt{3}\), realizing using the software Mathcad, we get the working area of the manipulator, which is a graphical display of the solution of the system of equations (10) formed by spherical surfaces as shown in Figure 7.

Thus from the working area of the spray nozzle in fig. 7, point \(K\) moves along the X axis from min \((x) = -446.4\ mm\) to max \((x) = 749\ mm\); Z-axis from min \((z) = -517.6\ mm\) to max \((z) = 517.6\ mm\); Y-axis to max \((y) = -900.5\ mm\).
3. Conclusion
As a result of the kinematic analysis of the robot-weeder with the function of the sprayer and fertigation, a rational center distance for the attachment of linear drives and the maximum departure of the point of attachment of the working part were obtained from the equations of geometric synthesis. The working area of the cutting working part of the robot-weeder was built and limitations were determined to prevent its falling into the dead position. A working area of the spray nozzle for chemical treatment of plants in rows was obtained. The application of the developed methods of calculation and design will allow one to reasonably choose the design parameters at the initial design stage.

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Conflict of Interest
The authors have no conflict of interest to declare.

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