Kinematic study of the weeding robot

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Abstract. The paper presents the rationale for the structure, the calculation of the geometric and kinematic parameters of the robot for point removal of weeds. The working area of the output link of the weeding robot was obtained, and limitations were determined to prevent its falling into the dead position.

1. Introduction
With the mechanical destruction of weeds, the cultivator's working parts (paws) process only the areas of row spacing, without affecting the weeds located in rows between cultivated plants. Besides, the larger size of the cultivated plant, the greater the likelihood of its damage during continuous cultivation of row spacing.

2. Geometric synthesis
To solve the problem of complete weeding both in row spacings and in rows, the design of a robot has been developed for point weed removal (figure 1).

Figure 1. Mobile weeding robot.
The mechanism of the robot is a flat mechanism of a parallel-sequential structure and has five degrees of mobility of the working arm - milling cutters, which are also the generalized coordinates $W = q = 5$ [1, 2].

In figure 2 shows the structural scheme of the robot.

![Figure 2. Structural scheme of the robot.](image)

The degree of mobility of the output link 9 of the robot [2]

$$W = 3n - 2p_5 - p_4 = 3 \cdot 9 - 2 \cdot 11 = 5$$

(1)

The optimal geometrical dimensions of the executive links and their attachment points to the base of the robot are determined from the conditions for the implementation of the required movement, the required service area and the limitations imposed by the parameters [3, 4]: distance between plants (d) and protective zone (e) as shown in figure 2. To obtain the required service area, which would cover a certain number of rows - when designing a construction worker, it is necessary to take the distance (a) between the attachment points of the actuator links 2, 3.
Figure 3. The design scheme of executive units 2, 3 (top view).

For the main geometric constraints in the synthesis of the robot on the basis of a flat mechanism we take the following indicators: the angle of the sector of coverage in the horizontal plane $\Theta \geq 90^\circ$; maximum departure of executive units $l_{\text{max}} > |l|$. The largest sector angle $\Theta$ is it turns out when the actuator length $l_3$ 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 with respect to the axis $Oy$, it is sufficient to consider its motion with a constant minimum length of the actuator $l_2$ and a change only $l_3$.

Taking the above assumptions ($l_2=\text{const}$), we obtain a flat replacement circuit with a swinging actuator $l_3$ and a rocker $l_2$. Then, when going from one extreme position $A_2$ to the other, $A_3$, the length of the actuator $l_2$ changes from $l_{2\text{min}}$ to $l_{2\text{max}}$, turning the actuator $l_3$ 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 rod stroke is the coefficient of the actuator elongation $k = l_{2\text{max}} / h$. For electric cylinders (actuators), the range of variation $k=1,56$ is subsequently taken.

It is important to consider that the performance of the mechanism and its efficiency factor largely depend on the pressure angle $\nu$, the angle between the axis of the actuator and the velocity vector of the point of application of force. The allowable pressure angle in lever mechanisms, in general, should not exceed $[\nu] = 60^\circ$. A rational in terms of dimensions scheme of the mechanism is realized under the condition $\nu_{\text{max}} = [\nu]$, but on the other hand, the smaller $[\nu]$, the smaller the friction loss in hinges.

From the equation of the vector contour [5] for the scheme shown in Figure 3, we get the expression

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

whose solution is

$$\Delta l = \frac{b}{2} + \sqrt{\frac{b^2}{4} - c}, \quad (3)$$

$$b = -4l_{3\text{min}} (k + 1) \cdot \sin\left(\frac{\alpha}{2}\right) \cdot \cos([\nu]) - \frac{\alpha}{2} / (2k + 1), \quad (4)$$

$$c = 4l_{3\text{min}}^2 \cdot \sin^2\left(\frac{\alpha}{2}\right) / (2k + 1). \quad (5)$$

After determining the solution of equation (2) is the center distance $a$

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

Substituting $l_{2\text{min}} = 700$ mm and $l_{3\text{min}} = 700$ mm - the size of the actuator, as well as $\Delta l = l_{2\text{max}} - l_{2\text{min}} = 450$ mm - the stroke of the actuator rod, we get $a = 646$ mm.

The angle of rotation of the actuator $\alpha$ depends on the angle of the sector of the capture zone $\Theta$ as

$$\alpha = \frac{\Theta + [\nu] - \pi / 6}{2}.$$

Based on all previously found parameters, we can determine the maximum departure of point A from the edge of the base [6].
\[ L_{\text{max}} = \sqrt{\frac{L_2^2}{L_{\text{max}}} - 0.25a^2} = \sqrt{1150^2 - 0.25 \cdot 646^2} = 1103.7 \text{ mm}. \]

### 3. Definition of service area

One of the tasks of the kinematic analysis of robot is to determine the configuration of the service area, which is the spatial aggregate movement of the point M (figure 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 \( l_2 \) and \( l_3 \) on the frame.

![Figure 4. The kinematic scheme of the robot.](image)

The coordinates of the point M of the working body in the absolute coordinate system \( O_{XYZ} \) are:

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

(9)

where \( X_A \) and \( Y_A \) - are the coordinates of point A, the connection of the actuator rods \( l_2, l_3 \).

The coupling equations (10) between the coordinates of point A, the lengths of the links \( l_2, l_3 \), and the relative positions of their attachment points are:

\[
\begin{align*}
l_2^2 &= X_A^2 + (Y_A - Y_B)^2 \\
l_3^2 &= X_A^2 + (Y_A + Y_B)^2
\end{align*}
\]

(10)
where \( Y_B \) - the actuator mounting coordinate \( l_2 \).

Thus, the dependence of the coordinates of the point \( M (X_M, Y_M, Z_M) \) from the lengths of the links \( l_k, k = 1 \div 4 \), and the coordinates of the attachment points of the actuators \( l_2 \) и \( l_3 \) takes the form:

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

The system of equations (11) is a solution of the direct task of kinematics and completely determines the theoretical possible range of displacements of the point \( M \) in space, that is, the working area of service of the robot, and also allows to formulate the conditions excluding its falling into the dead position [7].

The restrictions are imposed on the coordinate \( Y_B \) of the point of attachment of the actuators \( l_2 \) and \( l_3 \).

\[
\begin{align*}
l_2^2 - \left( \frac{l_2^2 - l_3^2}{4Y_B} \right)^2 & + \frac{l_3^2 - l_2^2}{2} - Y_B \geq 0 \\
Y_B & \geq \pm \sqrt{\frac{l_2^4 + 2l_2^2l_3^2 + 4l_2^2 + l_3^4 - 4l_2^2 + l_2^2 + l_3^2}{4}}
\end{align*}
\]

Knowing the parameters of the lengths of actuators \( l_{\text{min}} = 700 \text{ mm}, l_{\text{max}} = 1150 \text{ mm} \) and \( a = 646 \text{ mm} \) – the distance between attachment points of actuators \( l_2 \) и \( l_3 \) on the frame, coordinates \( Y_B = -Y_C = a/2 \), solving the system of equations (11) with the help of the Mathcad software package, we obtain the working area of the weeding robot, figure 5 [8].
Figure 5. The working area of the robot.

Thus, from the shape of the working area of the robot in Figure 5, it can be seen that the point M moves along the X axis from min (X) = 1321 mm to max (X) = 2254 mm; Y-axis from min (Y) = -644 mm to max (Y) = 644 mm; on the Z axis from min (Z) = 700 mm to max (Z) = 1150 mm.

4. Conclusions
As a result, the degree of mobility of the weeding robot was determined, from the equations of geometric synthesis, a rational axial mounting distance of actuators 2, 3 and the maximum departure of the point of attachment of the working body were obtained. The working area of the robot was obtained, and limitations were determined to prevent its falling into the dead position. The application of the developed methods of calculation and design will allow to reasonably choose the design parameters of a flat manipulator of a parallel-sequential structure at the design stage.

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