Definition of service area of agricultural loading robot with manipulator of parallel-serial structure

M E Nikolaev, I A Nesmianov and Zaharov E N
Volgograd state agrarian university, Volgograd, University avenue, 26, 400002, Russia.

mr.maks.nikolaev.1994@mail.ru

Abstract. For the mechanization of loading and transport work when harvesting vegetables packed in nets, the design of the loading manipulator on the mobile chassis is proposed. The design feature is that the component of the loading manipulator is a mechanism of parallel structure - a tripod. The required number of degrees of freedom of capture for the quality assurance of the process is substantiated.

1. Introduction
For mechanization of loading and transport operations when harvesting vegetables packed nets, proposed the construction of a loading manipulator on a mobile chassis. The design feature is that a component part of the loading manipulator is a parallel structure mechanism - tripod. The necessary number of degrees of freedom of capture is substantiated for the quality assurance of the technological process. The parameters determined the basic geometric dimensions of the links, allowing to provide the required service area and, accordingly, the capture width of the loading aggregate, which is not less than the width of its body.

The quantity of manual labor in agriculture when harvesting vegetable fruits products is up to 40%, and in some cases even longer. An analysis of the situation when cultivating onion- turnips shows that in most cases its collection is carried out in grids, in such containers vegetable products are manually loaded onto a vehicle and delivered to the consumer.

2. Structural analysis
To solve the problems of mechanization of loading and unloading operations and their automation, the design of the loading robot-manipulator of parallel-serial structure, installed on a self-propelled chassis (Figure 1)[1, 2].

A spatial parallelogram mechanism 1 is attached to the chassis frame, which ensures the horizontal position of the platform 2 at various angles of inclination. A manipulator-tripod 3 is attached to the platform 2, in the form of a triangular pyramid, and a controlled tick-borne grip 5 is suspended from its output link 4 (multi-movable hinge unit). The capture is self-locking and, under the action of gravity, always occupies a vertical position, which allows you to capture packaging with vegetables in the form of nets, installed vertically in the field. The manipulator-tripod provides gripper movement along the width of the body of a self-propelled chassis along three Cartesian coordinates x, y, z. A given degree of capture mobility is provided by the generalized coordinates of the manipulator, which are links of variable length. In this case, these are three cylinders of the tripod manipulator and the...
cylinder of rotation of the rocker arm of the parallelogram mechanism. Thus, the degree of mobility of the attachment point of the capture is $W = 4$.

![Figure 1. Robotic manipulator on a self-propelled chassis.](image)

The most important tasks in the development of parallel-serial structure manipulators include structural and parametric synthesis of rational kinematic schemes of such manipulators. One of the main requirements that determine the operability of the manipulators is to ensure the approach of the manipulator's working body to the required points of the service object with a given orientation of the working body. Excessive bonds or excessive mobility lead to loss of stability of the mechanical system, the likelihood of jamming, increased wear due to large pressure angles in the joints, therefore one of the most important tasks that must be solved is a rational justification of the mobility of the manipulator joints and the choice of their class $[3-5]$.

Using the well-known Somov-Malyshev-Chebyshev dependencies to determine the degrees of mobility of the mechanisms $W$, as well as the dependences for handling systems similar to the one considered and obtained in [6], the conditional optimization problem is formulated in the following form

$$
6n - 5p_3 - 4p_4 - 3p_5 = W(n, p_i),
$$

$$
p_3 + p_4 + p_5 \geq W + n_{\text{min}},
$$

$$
p_3 + 2p_4 + 3p_5 \geq W + 6k
$$

$$
k = \Sigma p_i - n,
$$

where $W(n, p_i)$ – is the objective function; $n$ – is the number of movable links of the mechanism; $p_i$ – is the number of kinematic pairs of $i$-th mobility; $k$ – is the number of independent Hohman circuits.

Based on the general statement of the problem of conditional optimization, given a specific value of the objective function $W = 4$, the system becomes completely definable and takes the form

$$
\begin{cases}
6n - 5p_3 - 4p_4 - 3p_5 = 4, \\
p_3 + p_4 + p_5 \geq 7, \\
p_3 + 2p_4 + 3p_5 \geq 22, \\
3 + n \geq 12,
\end{cases}
$$
With the chosen criterion minimization of the moving links \( n \rightarrow \text{min} \) with restrictions
\[ n > 0, \ p5 \geq 0, \ p4 \geq 0, \ p3 \geq 0, \]\nthe system is transformed to the form of the optimization problem
\[
\begin{align*}
\frac{2}{3}p_3 + \frac{5}{6}p_5 + \frac{2}{3}p_4 + \frac{1}{2}p_3 & \rightarrow \text{min}, \\
p_5 + p_4 + p_3 & \geq 7, \\
p_5 + 2p_4 + 5p_3 & \geq 22.
\end{align*}
\] (3)

To solve system (3), linear programming methods are applicable, while it is more convenient to bring it to the matrix form
\[
X = A^{-1}B
\]
where
\[
A = \begin{pmatrix}
\frac{5}{6} & \frac{2}{3} & \frac{1}{2} \\
1 & 1 & 1 \\
1 & 2 & 3
\end{pmatrix}, \quad B = \begin{pmatrix}
n - \frac{2}{3} \\
7 \\
22
\end{pmatrix}.
\] (4)

Then
\[
\begin{pmatrix}
p_5 \\
p_4 \\
p_3
\end{pmatrix} = A^{-1} \begin{pmatrix}
n - \frac{2}{3} \\
7 \\
22
\end{pmatrix} = \begin{pmatrix}
\frac{5}{6} & \frac{2}{3} & \frac{1}{2} \\
1 & 1 & 1 \\
1 & 2 & 3
\end{pmatrix}^{-1} \begin{pmatrix}
n - \frac{2}{3} \\
7 \\
22
\end{pmatrix}.
\] (5)

Due to the fact that there can be several solutions to (5), it is necessary to narrow the range of the results obtained by introducing restrictions, for example, setting constraints on kinematic pairs of class \( IV - p4 = 0 \) and restricting kinematic pairs of class \( III \) to one - \( p3 \leq 1 \) (Figure 1). Then the solution becomes unique: \( p_5 = 19, \ p_4 = 0, \ p_3 = 1 \). Thus, in the mechanism of the manipulator, one spherical hinge is needed at the attachment point of the gripper, and all other kinematic pairs will be single-moving (\( V_{\text{class}} \)).

3. Define and build a service area configuration
To solve the problems of mechanization of loading and unloading operations and their automation, has been developed a loading robot with manipulator parallel-serial structure mounted on a self-propelled chassis. When designing the manipulation mechanism, it is necessary to determine the laws of variation of the generalized coordinates \( q(t) \), which provide a given movement of the gripper with the transported object [7].

One of the problems of kinematic analysis of a loading robot is to build a service area. The service area is formed by the spatial displacements of point \( M \), at which the axes of three moving links of variable length intersect (Fig. 2). The main criterion in the formation of the service area is the specified width of the chassis and ensuring the movement of tick-borne grippers over the entire body area.

The generalized coordinates are the lengths of the manipulator links \( l_1, l_2, l_4 \) and the angle \( \beta \) (the angle of inclination of the space-parallelogram mechanism, depending on the length of the link \( l_4 \)).

The theoretical zone of possible displacements of point \( M \) depends on the ratio of the lengths of the links \( l_1, l_2, l_4 \) and on the location of their attachment points on the base.

To determine the trajectory of the motion of the point \( M \), two coordinate systems are taken - fixed \( OX'Y'Z' \) and moving \( OX,Y,Z \). To compose the equations of communication between the coordinates of the point \( M \), the lengths of the links and the location of their attachment points, we use the dependence between the coordinates of two points in space and the distance between them. These
equations belong to the considered scheme in the moving coordinate system $O_1X_1Y_1Z_1$ have the form [8, 9, 10].

\[\begin{align*}
X_{1M}^2 + Y_{1M}^2 + (Z_{1M} - Z_{1E})^2 &= l_1^2, \\
(X_{1M} - X_F)^2 + Y_{1M}^2 + Z_{1M}^2 &= l_2^2, \\
(X_{1M} - X_G)^2 + Y_{1M}^2 + Z_{1M}^2 &= l_3^2,
\end{align*}\]

Figure 2. Kinematic diagram of a loading robot with a manipulator parallel - serial structure.

where $X_{1M}, Y_{1M}, Z_{1M}$ are the coordinates of point $M$ in a moving coordinate system; $l_1, l_2, l_3$ - current values of the lengths of the links of the manipulator; $Y_F, X_G = Y_F, \sqrt{3}$ - constant, in the selected system, the coordinates of the attachment points of the manipulator links.

Having solved system (1), we obtain the dependence of the coordinates of the point on the lengths of links $l_1, l_2, l_3$ and the coordinates of the attachment points of the base of the manipulator:

\[
\begin{align*}
X_{1M} &= \frac{A - Y_F^2 + X_G^2}{2X_G}, \\
Y_{1M} &= \frac{l_2^2 - l_1^2}{4Y_F}, \\
Z_{1M} &= -\left[l_1^2 - \left(l_3^2 - l_2^2\right) \frac{(A - Y_F^2 - Y_G^2)^2}{16Y_F^2} \right]^{1/2}.
\end{align*}
\]

The transition from the moving coordinate system $O_1X_1Y_1Z_1$ to the fixed $OXYZ$ is determined by the dependencies:

\[
\begin{align*}
X_I &= X_0 + \alpha_1X_{1M} + \alpha_2Y_{1M} + \alpha_3Z_{1M}, \\
Y_I &= Y_0 + \alpha_1X_{1M} + \alpha_2Y_{1M} + \alpha_3Z_{1M}, \\
Z_I &= Z_0 + \alpha_1X_{1M} + \alpha_2Y_{1M} + \alpha_3Z_{1M}.
\end{align*}
\]
where $X_M$, $Y_M$, $Z_M$ - the coordinates of the point $M$ in a fixed coordinate system; $X_0, Y_0, Z_0$ - projection of a vector that determines the position of the beginning of the moving coordinate system in a fixed coordinate system; $(\text{direction cosines})$ - the projection of the unit vector of the moving coordinate system on the direction of the unit vector of the fixed coordinate system, which is determined by the scalar product.

$$\alpha_{sk} = \overrightarrow{l}_s \cdot \overrightarrow{l}_k \quad s, k = 1, 2, 3$$  \hspace{1cm} (9)

For the design scheme (1) $X_0 = 0; \ Y_0 = Y_0; Z_0 = 0$, matrix of guide cosines

$$\begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \varphi & \sin \varphi \\
0 & -\sin \varphi & \cos \varphi
\end{bmatrix}$$  \hspace{1cm} (10)

Then expressions (2) for the coordinates of the point $M$ in a fixed coordinate system take the form

$$\begin{align*}
X_M &= \frac{A - Y_F^2 + X_G^2}{2X_G} + AC \cdot \left( \frac{l_4^2 - AH^2 - AB^2}{2 \cdot AH \cdot AB} \right) + AH + CK \\
Y_M &= \frac{l_1^2 - l_2^2}{4Y_F} \\
Z_M &= -\left[ l_1^2 \left( \frac{l_3^2 - l_2^2}{16 \cdot Y_F^2} \right) - \left( A - Y_G^2 - Y_G^2 \right)^2 \right]^{\frac{1}{2}} + AC \cdot \left[ 1 - \left( \frac{l_4^2 - AH^2 - AB^2}{2AH \cdot AB} \right) \right]
\end{align*}$$  \hspace{1cm} (11)

Where $A = -l_1^2 + 0,5l_2^2 + 0,5l_3^2$.

The resulting system of equations completely determines the theoretical possible region of displacements of the point $M$ in space, i.e. the working area for servicing the truck loader, and also allows you to formulate conditions that prevent it from falling into a dead position [11-12].

The implementation of the algorithm for the formation of a service coverage zone is implemented in Mathcad.

**Figure 3.** The working area of the loading robot with manipulator parallel_SERIAL structure.
Conclusion
The structure of the loading robot manipulator mechanism is substantiated. A kinematic analysis was carried out and the zone and shapes of the working zone of the loader robot are justified. Figure 3 shows that point $M$ moves along the $X$ axis from $\min (X) = -932.068 \text{mm}$ to $\max (X) = 3079 \text{mm}$; along the $Y$ axis from $\min (Y) = -694.444 \text{mm}$ to $\max (Y) = 694 \text{mm}$; along the $Z$ axis from $\min (Z) = 0 \text{mm}$ to $\max (Z) = 2290 \text{mm}$, thereby ensuring full coverage of the entire body area across the width of the chassis. Roman $\min (Y) = -694.444 \text{mm}$ to $\max (Y) = 694 \text{mm}$; along the $Z$ axis from $\min (Z) = 0 \text{mm}$ to $\max (Z) = 2290 \text{mm}$, thereby ensuring full coverage of the entire body area across the width of the chassis.

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