Investigation of the configuration of a parallel manipulator for additive manufacturing of solid structures

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Abstract. The last decade has seen an increase in publications on mechatronic systems of parallel structure with flexible connections. Such manipulators are used in the field of videography of sports events and in crane structures for special purposes. The paper proposes and studies the question of the use of a parallel structure manipulator with flexible connections to create a complex of additive manufacturing of building structures. The basic structural schemes of kinematics of cable parallel manipulators are considered. The solutions of direct and inverse kinematics problems of parallel structures suitable for building additive systems are considered. The developed mathematical model of the kinematics of cable manipulators makes it possible to conduct further research on the implementation of the control system in real-time mode.

1. Introduction
Industrial manipulators can be classified into parallel and sequential. Sequential manipulators consist of links connected in series, each link has a given degree of mobility, and the grip of the manipulator has a direct mechanical connection with only one of the links. The classic representation of the sequential manipulator is the KUKA industrial robot manipulator of the KR CYBERTECH series. In parallel manipulators, the grip has a physical connection with more than one link; the movement of the grip is carried out due to the coordinated mutual changes in the lengths of the links. An example of a parallel manipulator is the Gough–Stewart platform and its modifications such as ROBOCRANE [1].

2. Parallel mechatronic structures with flexible connections
The class of parallel manipulators can be conditionally divided into mechatronic systems with rigid and flexible links. The classifying feature, in this case, consists in the particular description of the mathematical apparatus of the manipulator links. A manipulator with rigid (elastic) connections can adjust the directed force in both directions along the longitudinal axis of the link i.e. has the ability to push and pull the grip of the manipulator. A flexible link manipulator uses directional action in only one direction - along the longitudinal axis of the link. Steel or synthetic cables are usually used as flexible connections.

Systems with flexible connections have a number of disadvantages. The main problem of cable manipulators can be considered the complexity of ensuring high accuracy of movement of the grip. The links of cable systems are subject to fluctuations. Complex tasks have to be solved when designing cable winding (stacking) systems because to ensure the accuracy of positioning it is necessary to strictly control the length of the manipulator links.
Parallel cable manipulators, despite their inherent disadvantages, have a number of key features that make them unique. In tasks where it is necessary to implement a relatively large working area of the manipulator, more than 20 meters, while the positioning accuracy of the grip of 0.5-1 mm is acceptable, a parallel cable manipulator can be the optimal solution. When implementing projects with a large working area using a cable manipulator, it is necessary to clarify the weight that it is able to move. As the analysis of literary sources [2] shows, the optimal working conditions for a cable manipulator is the case of moving a relatively small load (payload). Working weight of the manipulator, as a rule, does not exceed 1000 kg and the larger the working area of the manipulator, the less will be the working weight.

Among the existing applications of parallel cable manipulators, the most effective and commercially successful is the development of video recording systems for sports broadcasts called "Spidercam". The "Spidercam" system is not only used for the recording of sports broadcasts, it is also used in scientific research in the field of agriculture [3]. "Spidercam" has become commercially successful due to the specific requirements of the task, namely a large working area of about 100 by 100 meters and a small weight of the video camera, about 20 kg, these conditions can be considered optimal for the use of a parallel structure cable manipulator.

Research in the field of parallel cable mechatronic systems began in the 90s of the last century and continues to the present. Over almost a 30-year history of research, many theoretical and practical problems have been solved, and commercial projects have been built using considered systems. Currently, the ongoing real-time is aimed at introducing of cable systems into the industry and solving specific applied problems, in those areas where it is possible to maximize the use of unique features of parallel mechatronic systems with flexible connections.

A promising area of application for parallel cable manipulators is the implementation of threedimensional additive systems for the production of volumetric structures from building mixtures of a concrete type. When solving this problem, it is necessary to implement a number of technical characteristics:

- organize an extensive working area, at least 50 to 50 meters and up to 10 meters in height;
- ensure ease of deployment of the manipulator structure, configuration, commissioning and subsequent dismantling without destruction of the main parts of the manipulator;
- ensure the positioning accuracy of the manipulator grip is not less than 1 mm.

3. Kinematic schemes of cable manipulators

Parallel cable manipulators are performed according to several kinematic schemes, the difference in which is in the number of used links (cables). In [4] one of the first classifications of parallel manipulators with flexible connections is given. The expression \( n = m + 1 \), where \( n \) is the number of degrees of freedom of the system, and \( m \) the number of cables, is true. A parallel cable manipulator can be considered fully defined if it has one more cable than the number of degrees of freedom. In a fully defined manipulator, all degrees of freedom can be controlled by the tension of the cables. Some papers [5] use terminology to classify cable manipulators into fully defined, insufficiently defined and overly defined. Insufficiently defined manipulators use gravity as an additional effect on the grip of the manipulator, in addition to the effort in the cables.

Figure 1a shows the conditional scheme of the manipulator, consisting of three links. Conventional symbols at points A’, B’ and F’ show the device of cable-laying machines with coils. The grip of the manipulator is located at point M, the cables are shown by a dotted line. The tension in the cables is shown by the vectors \( t_1 \ldots t_m \) of the vector \( f_p, m_p \) is a perturbation (swaying) effect. As can be seen from the figure, to achieve equilibrium under external influence \(( f_p, m_p)\) the cable manipulator must create positive forces in the cable balancing the applied impact.
Maintaining a stable position of the manipulator grip under the external influence has an impact on the accuracy of the manipulator and is an important issue to be investigated. The parallel cable manipulator is resistant to any external disturbance if positive tension is maintained in the cables. The minimum number of links required to build a manipulator with a 3-dimensional workspace is three, such a manipulator corresponds to the definition of an insufficiently defined system. Designs with four cables and more are used more often. In this paper, we study the kinetostatic schemes of parallel cable manipulators in order to determine the most effective one to be used as a system of additive production of solid structures.

4. The solution of kinematic problems of cable manipulators

The direct problem of kinematics for a 3-cable parallel manipulator.

Considering the solution of kinematics problems of a parallel cable manipulator, it is necessary to determine the initial conditions. The fundamental condition is the constancy of the distance between the points of coming-off of the cable from the coils of the cable layer.

Let us represent each of the cables as a vector, let’s put the beginning of the Cartesian coordinate system at point A, the lengths of the vectors are indicated , and , respectively. The inverse kinematic problem for a 3-cable manipulator is solved by finding the lengths of the vectors :

\[ L_i^2 = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2, \quad i = 1, 2, 3 \]  \hspace{1cm} (1)

The distance between the supports of the manipulator will be denoted, respectively \( A'F' = c \), \( A'B' = b \) and \( B'F' = a \). Now let us write the coordinates of the supports in the Cartesian system:

\[ (x_1, y_1, z_1) = (0, 0, H), \]  \hspace{1cm} (2a)

\[ (x_2, y_2, z_2) = (a, 0, H), \]  \hspace{1cm} (2b)

\[ (x_3, y_3, z_3) = (c \cos(\theta), c \sin(\theta), H). \]  \hspace{1cm} (2c)

where \( \theta \) is the angle between \( A'F' = c \) and \( A'B' = a \).

The lengths of the vectors \( L_i \) can be calculated:

\[ L_1^2 = x^2 + y^2 + (z - H)^2, \]  \hspace{1cm} (3a)

\[ L_2^2 = (x - a)^2 + y^2 + (z - H)^2, \]  \hspace{1cm} (3b)

\[ L_3^2 = (x - c \cos(\theta))^2 + (y - c \sin(\theta))^2 + (z - H)^2. \]  \hspace{1cm} (3c)

The solution of the direct kinematics problem of a 3-cable manipulator (Figure 1a) is shown in expressions 4a-4c.
Let us consider the solution of direct and inverse kinematics problems for a manipulator using 4 cables (figure 1b). In contrast to the 3-cable manipulator, in the 4-cable one, the racks with cable-laying machines form a quadrangle, which leads to a change in the mathematical calculations. We move the origin to the centre of a rectangular area with sides $AC = a$ and $AB = b$. Let's write down the coordinates in which the run-off points of the cable from the cable-laying machine are located.

The cable lengths are determined, as previously, by the formula (1), the solution of the inverse kinematics problem for the system in Figure 1b is shown in expressions (5a-d).

Solving the direct kinematics problem for a 4-cable manipulator:

$$x = \frac{1}{2a}(L_2^2 + a^2 - L_1^2),$$  \hspace{1cm} (4a) \\
y = \frac{1}{2c\sin(\theta)}\left( L_1^2 - L_3^2 - \frac{c\cos(\theta)}{a}(L_4^2 + a^2 - L_2^2) + c^2 \right), \hspace{1cm} (4b) \\
z = H - \left( L_3^2 - x^2 - y^2 \right)^{1/2}. \hspace{1cm} (4c)$$

When solving the direct problem for the manipulator in figure 1b, it is necessary to determine the three cables involved in setting the position of the grip. It is possible to determine the cables involved in the setting of the position of the grips by dividing the conditional space with vertices at points $A, B, C, D, A', B', C', D'$ diagonally into equal parts. In the case when the grip of the manipulator is in the area with vertices $A, B, C, A', B', C'$, active are cables $L_1, L_2, L_4$, etc. by analogy.

The lengths of cables $L_1, L_2, L_3, L_4$ for the manipulator scheme in figure 1c are determined similarly as for figure 1b by the formulas 5a-d. The coordinates of the cable-layers for the upper links are similar to those previously considered. Let's write down the coordinates for the lower links:

$$\left( x_5, y_5, z_5 \right) = \left( \frac{-a}{2}, \frac{-b}{2}, H \right), \hspace{1cm} \left( x_6, y_6, z_6 \right) = \left( \frac{-a}{2}, \frac{b}{2}, H \right),$$
As follows from the given coordinates $H'$ is the setting height of the lower link of the cable-laying machine, $H' \geq 0$. The cable lengths $L_5 - L_8$ are determined by the formulas:

\[
L_5^2 = \left( x + \frac{a_1}{2} \right)^2 + \left( y + \frac{b_1}{2} \right)^2 + \left( z - H + O \right)^2, \quad (7a)
\]

\[
L_6^2 = \left( x + \frac{a_2}{2} \right)^2 + \left( y - \frac{b_2}{2} \right)^2 + \left( z - H + O \right)^2, \quad (7b)
\]

\[
L_7^2 = \left( x - \frac{a_1}{2} \right)^2 + \left( y + \frac{b_1}{2} \right)^2 + \left( z - H + O \right)^2, \quad (7c)
\]

\[
L_8^2 = \left( x - \frac{a_2}{2} \right)^2 + \left( y - \frac{b_2}{2} \right)^2 + \left( z - H + O \right)^2. \quad (7d)
\]

The distance between the cable spooling gears of the lower and upper links: $O = H - H'$. It should be noted that the system in Figure 1c is overly defined; therefore, the solution to the direct problem coincides with solution 6a-c. Let us express the solution in the coordinate $z$ taking into account the design features of figure 1c:

\[
z = H - O + \left( L_i - \left( x - \frac{a_1}{2} \right)^2 - \left( y - \frac{b_1}{2} \right)^2 \right)^{1/2}. \quad (8)
\]

Figure 1c shows a simplified diagram that gives an understanding of the general structure of the manipulator; in reality, the cables of the manipulator usually do not converge at one point but are attached to a certain rectangular platform. In practice, the idealized conditions in which the solutions of kinematics problems are obtained are in most cases not feasible and special algorithms for correction and calibration of the manipulator should be used.

5. Conclusion

The structure shown in figure 1c is the most resistant to external disturbances, but it requires more resources for implementation. Considering the three structures of the parallel cable manipulator, we can conclude that for the implementation of the additive manufacturing system of building structures, the option in figure 1a is most preferable, as it is simpler and more economically optimal.

References

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