Investigation of possible paths to implement the planar 3RPR robot movement along a predetermined trajectory

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Abstract. The paper considers various possibilities for implementing the movement of a robot of the parallel structure along a pre-calculated trajectory. A computational experiment using a model of a planar 3-RPR mechanism with direct current drive electric motors made it possible to study the accuracy characteristics of the robot depending on the selected mode of changing the tasks of controlling the length of its drive links. During the experiment, various possibilities of realizing the movement of a parallel robot along a pre-calculated path were investigated. The best mode, ensuring a minimum of dynamic deviation of the actual trajectory from the given one, is now recognized as a uniform change in the tasks of the control loops of the length of the drive links in time using linear Lagrange interpolation.

1. Introduction

The automatic system used to control the parallel robot has a significant impact on its speed characteristics and positioning accuracy. Organization of controlling the movement of a parallel mechanism is an urgent task, the solution of which, for example, is devoted to [1–10]. The two-stage robot control method proposed earlier by the authors [11–12] provides for constructing, taking into account the existing restrictions, the optimal trajectory of the output link of the mechanism, and calculating the corresponding input coordinates for each point of this trajectory. This first stage of management is preparatory and is carried out in advance. During the second stage, the calculated values of the input coordinates of the mechanism are used as tasks in the control loops of the state of individual drive links. As a result of a synchronous change in the input coordinates of the mechanism following the task, the optimal trajectory of motion constructed at the first stage is directly realized. Such a synchronous change can be made at predetermined equal or unequal time intervals or as the next points of the trajectory are reached with a given accuracy. The study aims to determine the best mode for changing the tasks of the control contours of the input coordinates of the parallel robot.

2. Control system of a planar 3RPR robot

The objective of this study was solved using the example of a planar 3-RPR robot (Figure 1).
Rods of variable length are pivotally attached to a non-movable base at points A1, A2, and A3, and to a movable platform at points B1, B2, and B3. The input coordinates of the mechanism are the lengths of the rods (l1, l2, l3), which vary under the action of direct current drive electric motors, the output coordinates are the position (x, y, \( \phi \)) of the center C of the moving platform in the coordinate system associated with the stationary base. A control system model in the MATLAB environment was developed (Fig. 2). It is necessary to submit tasks for the control loops of the lengths of the corresponding rods to follow the selected path to the Target inputs of the LEG-1, LEG-2 and LEG-3 sub-systems. Each of the rods (Fig. 3) consists of two rods connected by a Prismatic Joint. The opposite end of one of the rods is attached to a fixed base using the Revolute Joint, and the other to a movable platform. Direct current drive electric motor is used to change the length of the rod. The engine is controlled using the Controlled PWM Voltage and H-Bridge units. The rotational motion of the motor shaft is converted into a translational motion of the hinge using a screw-nut gear (Leadscrew unit). To match the applied force and speed of movement of the drive joint, the Prism-Trans Interface block has been developed. The hinge position signal is used to provide feedback. The status signals of the swivel joints are taken in the LEG-3 sub-system to quickly calculate the position of the mechanism moving platform centre and construct the trajectory of the system in the output coordinates (x, y).

**Figure 1.** The planar 3RPR robot  
a – structural scheme; b – robot design

**Figure 2.** Model of a planar 3-RPR robot control system

**Figure 3.** Model of the contour control rod length (sub-system LEG-3)
In the output coordinates of the mechanism (x, y), the path chosen for the experiment is a circle with a radius of 60 cm, the center of which coincides with the center of the fixed base. We set the trajectory in the form of three masses of rod lengths (input coordinates), determined by solving the inverse problem of kinematic analysis of the mechanism:

\[
l_1^2 = (x + 0.5r(\sin \varphi - \sqrt{3}\cos \varphi) + 0.5\sqrt{3}R)^2 + (y - 0.5r(\sqrt{3}\sin \varphi + \cos \varphi) + 0.5R)^2
\]

\[
l_2^2 = (x + 0.5r(\sin \varphi + \sqrt{3}\cos \varphi) - 0.5\sqrt{3}R)^2 + (y + 0.5r(\sqrt{3}\sin \varphi - \cos \varphi) + 0.5R)^2
\]

\[
l_3^2 = (x - r\sin \varphi)^2 + (y + r\cos \varphi - R)^2
\]

where R and r - radiiuses of the circles described near the triangles A_1 A_2 A_3 and B_1 B_2 B_3, respectively. Switching tasks (steps of the trajectory) must be synchronous and can be carried out, for example, at regular intervals. Simulation showed that the lengths of the mechanism rods, in this case, correspond to the specified ones (Figure 4). Its trajectory in the output coordinates is visually indistinguishable from the circle. The following accuracy was estimated by the deviation from the assignment of the output coordinates, by determining the distance from the center of the fixed base (0, 0) to the current point (x, y) and comparing it with the given radius of the trajectory In contrast to [11], The graph of the dynamic deviation (Figure 5) shows that for the case of switching tasks at equal intervals of time, the maximum modulus of the dynamic error is less than 0.3 mm, i.e., less than 0.05% of the radius of a given circle.

3. Determination of the optimal mode for changing tasks

The first of the proposed changes is aimed at overcoming the shortcomings of the transition process caused by the discrete (stepwise) nature of the job shift. The use of linear Lagrange interpolation in itself does not lead to a significant change in the initial dynamic error graph, but it allows adjusting the coefficients of the regulators to reduce it (Figure 6, the blue graph - without interpolation, red - linear interpolation, blue - the regulator parameters are additionally corrected). Without interpolation, this is not possible. Besides, the interpolation application reduces the error that occurs when the drive inertia increases (Figure 7, blue - the initial system, red - the parameters of the regulators are corrected, blue - interpolation without correction, purple - interpolation with correction).

The important drawback of the used task change mode is its uniformity: the same time is allotted for each step of a given trajectory. This circumstance leads to a decrease in the speed of the robot, since if during the step there is a smaller change in the lengths of the links, less time can be spent on it. It is
necessary to determine the step duration to organize the process of switching tasks in time, taking into account the maximum along all control loops, changes in the length of the links:
\[ \Delta t_i = \Delta t_0 \cdot \max_j (\Delta l_{ij}) / \max_{ij} (\Delta l_{ij}), \]
where \( \Delta l_{ij} \) is the increment of the rod \( j \) during the \( i \)-th step, \( \max_j (\Delta l_{ij}) \) is the maximum increment of the rod during the \( i \)-th step (for all rods), \( \max_{ij} (\Delta l_{ij}) \) is the maximum increment of the rod during the step (for all rods and all steps), \( \Delta t_0 \) is the time sufficient to move to \( \max_{ij} (\Delta l_{ij}) \).

The application of this formula allows reducing the duration of working out a given trajectory (Figure 8 and Figure 4), but the dynamic error increases. However, it can be slightly reduced by adjusting the parameters of the regulators (Figure 9, blue - the original system, red - the duration of the step is changed, blue - the parameters of the regulators are additionally corrected).

The increase in the error value (blue graphs in Figure 9 and Figure 6) is caused by the fact that the maximum possible speed of the electric drive is unstable and depends on the specific position of the mechanism and the operation of other drives. In addition, in reality, it will be affected by the load that occurs during the processing of the product.

Another way to account for the variable step duration is to switch tasks as they reach the next path points. It should be noted that its application introduces uncertainty into the question of the duration of trajectory processing. The advanced operational management algorithm provides:
- loading the trajectory \( C(K, 3) \), where \( K \) is the number of steps, 3 is the number of rods;
  - cyclically for each iteration \( (i = 1..M) \):
    - initialization of the Boolean flag \( F \);
    - cyclically for all length control loops \( (j = 1..3) \):
      - interrogation of sensors \( D(j) \),
      - calculation of the current task (interpolation):
        \[ C_1 = C(i \cdot K / M, j) + (C(i \cdot K / M + 1, j) - C(i \cdot K / M, j)) \cdot (i \cdot K / M - [i \cdot K / M]), \]
        where square brackets mean taking the integer part of a number,
    - mismatch calculation \( E(j) = C_1 - D(j) \),
    - regulation
    - output \( U(j) \) to actuators,
    - checking the magnitude of the error \( |E(j)| < e \), calculation of \( F \);
    - the condition for the transition to the next iteration \( i \) is the truth of \( F \) after the completion of cycle \( j \), i.e. achievement of the current task along all length control loops with a given accuracy.

The modification of the algorithm compared to [11] consists of the use of interpolation. The algorithm was implemented in MATLAB using Simulink blocks. The outputs of this sub-system are connected to the Target inputs of the LEG-1, LEG-2, and LEG-3 sub-systems. Signals from the corresponding outputs of the same sub-systems are fed to the Result inputs. By varying the values of the permissible control error (relay sensitivity) and the step size (due to interpolation, it can be significantly reduced), one can significantly limit the error in regulating the length of the links. However, the dynamic error of the trajectory processing increases somewhat (Figure 10, blue - the initial system, red - the parameters of the regulators are corrected). This result is explained by the fact that a small change in the lengths of the links does not always correspond to equally small changes in the output coordinates.
5.

Figure 10. Error switching tasks as trajectory points are reached

It may be recommended to check dynamic errors by the output coordinates of the mechanism to increase accuracy, instead of checking the magnitude of the control error in each circuit. This will require solving the direct problem of the kinematics of the mechanism, however, as it is shown in the work [10], such a problem can be successfully solved on the basis of a neural network model of the mechanism.

4. Conclusions

A model of a planar 3-RPR mechanism with direct current drive electric motors developed in MATLAB is presented. During the experiment, various possibilities of realizing the movement of a parallel robot along a pre-calculated path were investigated. The best mode, ensuring a minimum of dynamic deviation of the actual trajectory from the given one, is now recognized as a uniform change in the tasks of the control loops of the length of the drive links in time using linear Lagrange interpolation. In order to further increase the speed of the robot and limit dynamic errors during further research, it is supposed to check the feasibility of organizing task switching as the next points of the trajectory of the output link of the robot are reached.

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