Scheduling system for programed manipulator motion pattern of the parallel structure with flexible links

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Abstract. The use of manipulators with various designs has been recently increasing in the industry. The main construction types of manipulators are considered to be serial and parallel structures. In turn, parallel manipulators can be divided into flexible and rigid joints. The use of manipulators with parallel structures and flexible links in a number of industry fields can increase operational performance, but this type of manipulator remains the least studied. In the present research, an attempt is made to consider a method for planning the motion pattern of a manipulator gripper with parallel structures and flexible links. Planning the movement pattern of the gripper is determined by the DDA algorithm (digital differential analyzer). The problem of forming the control actions on the automatic control system of the electrical drive for the links of the manipulator is considered. The results of full-scale modeling on a real model of a cable parallel structure manipulator are presented. The general functional diagram of the manipulator control is also considered in the research.

1. Introduction
Cable manipulators with a parallel structure have many potential advantages over classical (serial) manipulators, including a larger working area, accuracy, and most importantly higher useful load factors. Cable structures are able to provide work in a much larger area compared with traditional parallel manipulators with a rigid joint. In addition, their relatively low mass and inertial rates make it easier to work at higher speeds. However, there is a distinguishing feature of such designs, cables can pull, but not push, which leads to one-sided limits that complicate modeling and analysis of manipulators with flexible joints. The manipulator with a parallelepiped-shaped service area is considered in the paper. The kinematics of the manipulator in this case is redundant. The full control of all freedom degrees by the control system of the cable manipulator can be provided if the cables always remain tense, which makes special demands on the manipulator control system. Cable robots also suffer from a limited resistive torque (impact). In order to combat these limitations, various methods have been proposed in the scientific literature, each has its own advantages and disadvantages [1].

The goal of the research is to develop a system for planning a programmatically specified moving pattern for a gripper of a manipulator with a parallel structure. Also, the options for program implementation of the control process when centrally generating control actions for the electric drive on links from a single control device are developed. The control is based on parallelizing the trajectory calculation between the digital control systems of each of the manipulator’s electric driver links.
The paper considers an option for implementing the programme control shell for a personal computer that implements both of the proposed methods for the formation of control actions on the electric drive of the manipulator links. The manipulator has a parallel structure with flexible links.

A general view of a manipulator with flexible links is shown in Figure 1.

![Figure 1. A general view of a manipulator with flexible links.](image)

The following legend is adopted in Figure 1:
- Ch1, Ch2, Ch3, Ch4 – bearing pulleys of the manipulator’s links;
- L1, L2, L3, L4 – working lengths (generalized coordinates) of manipulator’s links 1-4, respectively;
- r1, r2, r3, r4 – reduction radii of gear motors in electric drives of manipulator links;
- V1, V2, V3, V4 – linear rates of changing the working lengths of manipulator’s links 1-4, respectively;
- ω1, ω2, ω3, ω4 – angular speeds of the electric drives of the manipulator’s links 1-4;
- M (x, y, z) – position of the manipulator’s gripper in the absolute coordinate system.

The kinematic structure presented in Figure 1 can be described as follows:
- the service area of the manipulator is represented by АВСDА1В1С1D1;
- at points A, B, C, D inextensible threads are carried by bearing pulleys, and their free ends are interconnected at point M, which is the fastening point of the cargo of mass m;
- the second ends of the threads are fixed on the drums of the gear motors, with their help the length of each manipulator’s link L1÷L4 is changed;
- coordinates of points A(x1, y1, z1), B(x2, y2, z2), C(x3, y3, z3), D(x4, y4, z4) in a Cartesian coordinate system, the origin of which coincides with point A, are known, and the following was adopted for the calculated kinematics:
  \[ x_1 = x_2 = 0, \ y_1 = 0, \ y_1 = y_2, \ z_1 = z_2 = z_3 = 0; \]
- a change in the Cartesian coordinates of point M in a given spatial domain is achieved by changing
the lengths of the threads L1÷L4 between points A, B, C, D and point M, respectively.

The task of forming control actions for the electric driver’s links can be formulated as follows:
- a trajectory section is defined in space as a segment of a straight line or circular arc;
- the absolute coordinates of the gripper’s position and the generalized coordinates of all links at the beginning and end of the trajectory fragment are known;
- the current values of the generalized coordinates are available for measurement at any point of the movement pattern;
- the movement speed along the trajectory and the sampling rate of the formation of control actions by speed on the link driving system are set.

The solutions of the direct and inverse kinematics problems in position and velocity for the structure presented in Figure 1 are exposed in the researches [2, 5]. According to the figure, two methods for planning the movement pattern are proposed, one of which has a significant methodological error in accuracy, the second makes high demands on the speed of hardware and software platform that provides a manipulator control system.

In order to solve the considered problem, the use of a digital differential analyzer (DDA) algorithm is proposed in the research, which is widely used in CNC systems.

The movement pattern can be specified in the form of a text file of the program in G-codes or using the programme control shell of the manipulator control system. In the second case, the trajectory parameters are set visually or numerically using the shell graphical interface.

Thus, solving the problem can be divided into three stages:
- determining the interpolation parameters of the trajectory fragment in the Cartesian coordinate system;
- calculating the current increments of the specified Cartesian coordinates along the movement pattern;
- the specified values of the generalized coordinates are determined according to the calculated values of the Cartesian coordinates of the given position;
- output of the specified values of generalized coordinates to the automatic control system (ACS) of the manipulator’s driving system of links;

The source code of C language programs that implements the CDA algorithm in real time for a segment of a line on a plane is widely represented on the Internet. Adapting the program text for a straight line segment in space does not cause significant difficulties.

The values L1-L4 are used as a task on the ACS of electric drives of links. System (1) is redundant for describing the current position of the gripper of the manipulator. Moreover, due to the non-ideal design, the unstressed link may not be identical to the corresponding equation of system (1).

$$\begin{align*}
L_1 &= \sqrt{x^2 + y^2 + z^2}; \\
L_2 &= \sqrt{(x_2 - x)^2 + y^2 + z^2}; \\
L_3 &= \sqrt{(x_3 - x)^2 + (y_3 - y)^2 + z^2}; \\
L_4 &= \sqrt{x + (y_3 - y)^2 + z^2}. 
\end{align*}$$

The values L1-L4 are used as a task on the ACS of electric drives of links. System (1) is redundant for describing the current position of the gripper of the manipulator. Moreover, due to the non-ideal design, the unstressed link may not be identical to the corresponding equation of system (1).
Figure 2. The horizontal projection of the manipulator’s service area.

There are two sub zones in the horizontal plane of the ABCD service area described by ∆BAD and ∆BCD (Figure 2) when moving the gripper of the manipulator along the straight line MN. The equation system (1) is redundant for solving the planning problem in each of the zones, in this case one of the equations can be excluded. For ∆BAD, these are equations 1, 2, 4 of system 1, and for ∆BCD these are 2, 3, 4. Therefore, it is necessary to continuously determine the affiliation of the current trajectory point to one of the zones when solving the problem of planning the trajectory in real time. If ∆BAD is adopted as basic, then the results of the calculating the following expressions are:

\[(x_d - x_i) \cdot (y_B - y_i) - (x_B - x_d) \cdot (x_d - y_i),\]
\[(x_B - x_i) \cdot (y_D - y_i) - (x_D - x_B) \cdot (x_B - y_i),\]
\[(x_D - x_i) \cdot (y_A - y_i) - (x_A - x_D) \cdot (x_D - y_i).\]

This allows concluding that the point belongs to a specified area. If the calculation results for all three expressions have the same sign, then the point \(x_i, y_i\) belongs to ∆BAD, otherwise to ∆BCD.

Thus, the problem of the point belonging to the trajectory of one of the service area parts should be additionally solved at each step of the trajectory interpolation.

The block diagram of the control system that implements the presented trajectory planning algorithm is shown in Figure 3. The upper hierarchy level is implemented in software using a personal computer (PC). Each link of the manipulator includes an ACS of an electric drive, implemented on the microcontroller basis, an electric motor, a gearbox, a drum, and the executive cable link itself. The practical implementation of solving the problem of planning the manipulator’s gripper movement pattern can be presented in two options.

The first option involves solving the problem at the top level of the management hierarchy. The interpolation step is determined based on the ACS design features of the electric drive. The minimum step in the implemented version of the manipulator can be selected based on the resolution of the optoelectronic encoder (angular position sensor) attached to the electric motor shaft of the manipulator link. Moreover, the minimum pitch in the implemented design can be taken equal to 0.154 mm. However, this step cannot be implemented due to insufficient high-speed performance of a PC running the Windows 7 operating system. Therefore, an interpolation step of 1 mm was adopted, which is quite acceptable for a service area of 2300x1100x2500 mm.
The minimum 50 ms time interval of the interpolation step is adopted, which allows achieving the maximum gripper movement speed 1.2 m/min. The entire procedure for the formation of the control action on the ACS of the electric drive of each link is carried out by software. The trajectory and movement speed along the trajectory are set from the graphical interface of the programme shell of the PC. The increments for each of the generalized coordinates at each interpolation step are transmitted over the serial Ethernet interface in accordance with the UDP protocol.

Information on the current state of link parameters (current and true values of generalized coordinates, movement speed along a generalized coordinate, effort in a link) is cyclically transmitted through the interface from each link. Information about the current values of the given position for each of the generalized coordinates is transmitted asynchronously as the next interpolation step is calculated. The UDP protocol does not provide guaranteed delivery of an information packet, which, according to the pilot operation of the considered manipulator, leads to separate, relatively rare, failures and blocking of the movement along the trajectory.

There are two ways to eliminate abovementioned drawback:
- use the TCP / IP protocol;
- transfer the interpolation procedure to the lower level of the control hierarchy and parallelize the solution of the problem between microcontrollers that implement ACS for the electric drivers of the manipulator’s links.

Using a high-level protocol complicates the software implementation of the software, especially the lower level of the control hierarchy.

The implementation of the second method does not cause significant difficulties, since part of the program code with minor changes can be transferred to the level of the ACS microcontroller. In this case, starting the procedure for working out the movement of the gripper along a given trajectory requires the PC to transmit only four packets containing the specified motion parameters. Those parameters include the interpolation step for each coordinate, the speed of movement along the leading Cartesian coordinate. At the same time, the speed is transmitted in unsigned int format, the leading coordinate signed int, the slave coordinates in float format.

**Figure 3.** The structural diagram of the control system.
Figure 4. Functional diagram of the ACS position of the manipulator’s link.

The following legend is presented in Figure 4:
CB - control box;
PWC - pulse-width converter;
GM - gear motor;
CS - sensor of the motor armature current;
PS - sensor of the angular position of the motor shaft;
ES - sensor of the effort in the link;
D – the drum.

The control function of the measurement process is directly performed by the CB controller, created on the basis of the STM32 family microcontroller with the ARM Cortex-M3 core and a clock frequency of 100 MHz. The microcontroller includes a multi-channel twelve-bit AD encoder with a conversion time of 1 μs, 14 timer-counters that allow programming or measuring time intervals with an accuracy of 4 ns regardless of the operation of the computing core, as well as hardware support for a number of serial interfaces including Ethernet.

The high-torque motor with a gearbox (Mr) was selected as a drive for the drum D of each of the manipulator’s links. The motor’s excitation is from permanent current magnets SF8156 P = 250 W; U_k = 24 V; n_n = 2200 rps; n_a = 1830 rps; I_u = 10 A; M_n = 1.3 N⋅m, R_y = 0.41 Ohm, gear ratio of the gearbox i=10, moment of inertia of the electric motor, including the gearbox J =0.00595 kG·m².

The XVX chip with galvanic separation based on the Hall effect is used as a current sensor. Normalized characteristics were tested during microcontroller operation in the mode of converting an analog signal to digital in the full variability range from +20A to -20A for an active load. The current value was directly measured by a measuring shunt and is 30A, 75mV using a precision M45mzz millivoltmeter. The time for converting current to voltage for this type of sensor does not exceed 5 μs; therefore, the current sensor can be represented as a linear inertialess link.

An optoelectronic encoder 20S with a resolution of 1024 pulses per revolution is used as a speed sensor in the system represented in Figure 4. The speed is measured using the length of the period
between two adjacent encoder pulses. The encoder shaft is mechanically connected to the motor shaft by means of a cardan drive. The gear ratio of this connection is $i=1$. The upper speed limit for the adopted reduction radius $s_{rad} = 57.7 \text{ rad/s}$. At a filling frequency $f_c = 25 \text{ MHz}$, the rotation speed can be determined according to the following relation

$$ \Omega = \frac{25 \cdot 10^6}{1024 \cdot N_f}. $$

(2)

The accuracy of measuring speed near the upper limit of the measuring range is not worse than 1 Hz. The low end is limited by the rotational speed of the motor shaft, which is 0.3 rps. If operating at low speeds is required, the numerator of the expression (xx) can be reduced by 10,100 or more times. At the same time, in order to maintain accuracy in the entire range of 0–9 rps, it is necessary to introduce several sub-ranges of measurement.

When implementing the interpolation process at the microcontroller level of ACS of electric drives, their computing power allows the interpolation time interval to be implemented at a level of 50 μs. This significantly exceeds the limiting speed of the manipulator’s gripper along a given movement pattern.

However, the interpolation process is out of sync, which can lead to an oscillatory process when moving along a trajectory. Synchronization of the interpolation process between ACS units can be based on the exchange of information in the control system of the manipulator. A visual representation of the procedure for exchanging information on the system interface is presented in Figure 5.

![Figure 5](image)

**Figure 5.** The procedure for exchanging information via the system interface.

In accordance with this procedure, a closed ordered cycle of information transfer from the ACS of the manipulator’s links is formed. Data packets are transmitted sequentially one after another. The transmission end of the previous packet initiates the transmission of the following one, which significantly reduces the risk of packet loss. A temporary pause (MO) is included in the cycle body of the transmission, which allows seamlessly inserting data packets from the top level of the control hierarchy.

The size of the data packet is 20 bytes, including the header. Assuming a timeout value equal to the transmission time of one data packet, the frequency of the complete transmission cycle will be 7.5 kHz at a data transfer rate of 7.5 Mb/s over the communication channel. This process can be synchronized by accepting the calculation of the next interpolation step at the transmission end of the data packet of the first link for all links. At the same time, by using this frequency as a reference at an interpolation step of 1 mm, it is possible to obtain a range of changes in the movement speed of the gripper within 0 – 7.5 m/s.

The proposed method for planning the gripper movement pattern for the manipulator with a parallel structure and flexible links was tested on a prototype. The process of trial operation revealed the full operational capability of the proposed planning method. The maximum deviation from the given
trajectory at $V_T = 200$ mm/s was $\Delta l_{\text{omax}} = 5$ mm. At $V_T = 50$ mm/s, the value of the relative error ranges from plus to minus 4 discrete measurements of generalized coordinates (one discrete is 0.154 mm).

2. Conclusions
One of the methods for planning the movement pattern of the manipulator’s gripper is considered. It is based on the DDA algorithm, as well as on parallelizing the calculating process of the current increments of relative coordinates between ACS of the electric drives in the manipulator’s links. The error value of the method and the factors affecting it are determined. The results of full-scale modeling on a real device layout are presented. The proposed design of the manipulator can find application in many industrial areas [2,3,4]. The main advantage of the kinematic scheme considered in this work is the possibility of expanding the service area in the horizontal plane to one hundred meters or more. In particular, the presented manipulator can find application in agriculture in order to determine the current soil parameters over a large area.

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