Synthesis of Control Algorithm and Computer Simulation of Robotic Manipulator-Tripod

Ivan Nesmianov[1], Victor Zhoga[2], Vladimir Skakunov[2], Stanislav Terekhov[2], Vitaly Egunov[2], Natalia Vorob'eva[1], Victor Dyashkin-Titov[1], and Fares Ali Hussein Al-hadsha[3]

[1] Volgograd State Agrarian University, Volgograd, Russia
ivan_nesmiyanov@mail.ru
[2] Volgograd State Technical University, Volgograd, Russia
{zhoga,svn}@vstu.ru, {set1091994,vegunov}@mail.ru
[3] Sana'a University, Marib College (Faculty of Sciences), Marib, Yemen
alhadsha@mail.ru

Abstract. This paper examines the way to increase the efficiency of functioning of the manipulator-tripod on a rotary base by mean of improving the control algorithms of the drive links. The algorithms of kinematic and power analysis of manipulator-tripod have been developed. The problem of optimal programmed path synthesis from the condition of minimum gripper arm was solved. Control system was developed with the feedback by position that solves the problem of contour's control. The results of numerical experiments and field modeling of developed control algorithms of drive links are presented.

Keywords: manipulator – tripod, gripper arm, kinematic and power analysis algorithms, optimal control, the control system.

1 Introduction

In the manipulators based on the parallel structure mechanisms (PSM) features of metallic constructions and drives are combined. So they take a load like spatial farms, and as a consequence, have higher positioning precision with high gripper speed and acceleration. Manipulator with parallel structure mechanisms compared to manipulator with the series-connected links, is characterized by high load capacity and relatively small metal consumption [1]. Such manipulators can be mounted on mobile robots for monitoring and forecasting the state of the environment, prevent and eliminate environment pollution, elimination of emergency situations of natural and technogenic character. They can help produce handling and transport work, deliver technical means and materials in the work area, conduct engineering work on the cleanup and dismantling of dilapidated structures, demining, collection and transportation of hazardous facilities [2-5].

The disadvantages of parallel structure manipulators are limited working area, a small manipulative, lack of optimal control algorithms [6].

A. Kravets et al. (Eds.): CIT&DS 2015, CCIS 535, pp. 391–403, 2015.
DOI: 10.1007/978-3-319-23766-4_31

In this regard, the optimization of geometrical, kinematic and power parameters of parallel kinematic structure manipulators and development of their calculation and design methods are actual tasks.

2 Manipulator – Tripod

The basis of the manipulator is spatial actuator mechanism in the form of a triangular pyramid with links of variable length as executive links (Fig. 1).

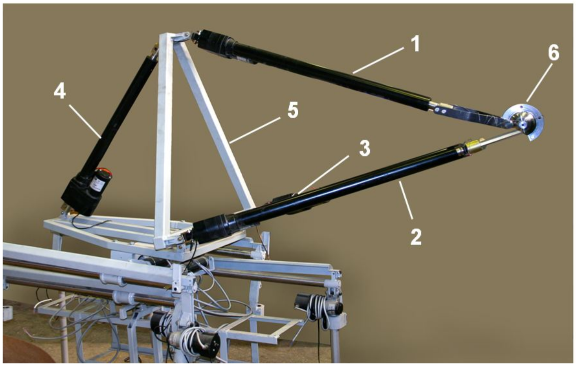

Fig. 1. The design of the manipulator-tripod

The mechanism contains three variable-length links 1, 2, 3 the ends of which are fixed by means of special two-movable hinges on the rotary base 5 that allows to change the service area. Opposite ends of the links are connected with a special hinge 6, providing the intersection of the geometrical axes of these links at one point and eliminating bending moments from external loads. Rotary base 5 has the ability to turn around due to the variable-length link 4 [7].

3 Kinematics of the Manipulator

Fig. 2 is a block diagram of the manipulator, wherein the linear movement axes geometrically converge via the universal spherical five-flexible pivoting unit.

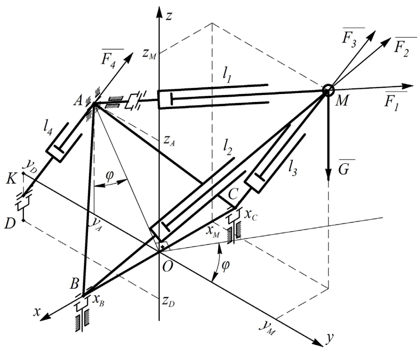

Fig. 2. The scheme of the manipulator-tripod on the rotary base

As an executive cylinders are presented in the form of links with V class kinematic pairs, in the points of their fastening two-movable hinge nodes are set, and the number of manipulator degrees of freedom is 3.

The Cartesian coordinates in the absolute system of reference $Oxyz$ (Fig.2) are accepted as generalized coordinates of capture. Generalized coordinates of the manipulator are the link lengths $l_k(t)$=1$\div$4.

Equations relations between the generalized coordinates and the lengths of the links $l_k(t),\ k=1\div 4$ are of the form

$$
\begin{gathered}
l_1(t)=\sqrt{x^2+(y+OA\cdot\sin\varphi)^2+(z-OA\cdot\cos\varphi)^2}\,,\\
l_2(t)=\sqrt{(x-OB)^2+y^2+z^2}\,,\\
l_3(t)=\sqrt{(x+OB)^2+y^2+z^2}\,,\\
l_4(t)=\sqrt{(OK-OA\cdot\sin\varphi)^2+(OA\cdot\cos\varphi+DK)^2}\,,
\end{gathered}
\qquad (1)
$$

where OA, OB, OK, DK - geometrical parameters of the manipulator base and its mounting points on the rotary base (Fig. 2); $\varphi(t)$– the angle of inclination of the manipulator base.

To build the theoretical service area of the manipulator we use the algorithm for constructing trajectories, forming the service area, with restrictions on the stroke of the actuators and rotation angles of the links in the joints [8]. Trajectories of gripper points form six spherical surfaces, the intersection of which characterize its limit positions in which the directions of movement of the link stocks of the spatial mechanism change (Fig. 3). Parametric equations of the trajectory of gripper are determined by the solution of the direct kinematic problem and are used to construct the theoretical service area of the manipulator

$$
\begin{cases}
x(t)=\dfrac{l_3^2(t)-l_2^2(t)}{4\cdot OB}, \\[2ex]
y(t)=\left(l_1^2-\dfrac{\left(l_3^2(t)-l_2^2(t)\right)^2}{16\cdot OB^2}-\dfrac{\left(A-OB^2-OA^2\right)^2}{4\cdot OA^2}\right)^{\frac{1}{2}}\cdot\cos\varphi-\left(\dfrac{A-OB^2+OA^2}{2\cdot OA}\right)\cdot\sin\varphi, \\[2ex]
z(t)=\left(l_1^2-\dfrac{\left(l_3^2(t)-l_2^2(t)\right)^2}{16\cdot OB^2}-\dfrac{\left(A-OB^2-OA^2\right)^2}{4\cdot OA^2}\right)^{\frac{1}{2}}\cdot\sin\varphi+\left(\dfrac{A-OB^2+OA^2}{2\cdot OA}\right)\cdot\cos\varphi,
\end{cases}
\qquad (2)
$$

where $A=-l_1^2(t)+0{,}5l_2^2(t)+0{,}5l_3^2(t)$.

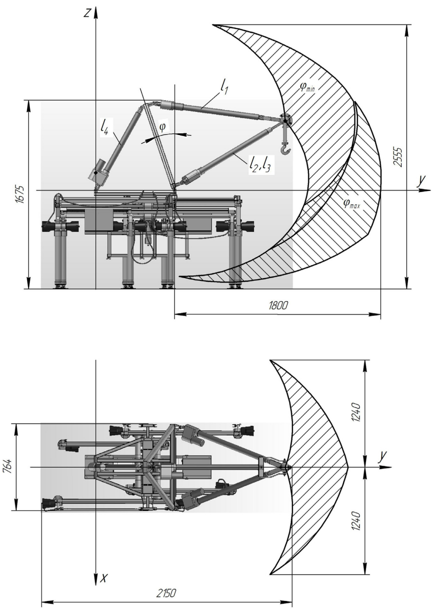

Fig. 3. The service area of the manipulator - tripod

4 The Dynamics of the Manipulator

In order to determine the forces in the executive links of the manipulator (Fig. 4) and their kinematic characteristics the model of the dynamics of the manipulator–tripod is developed. To simplify the differential equations describing the dynamics of the manipulator, the real mechanism is replaced by a dynamically equivalent with two concentrated masses: m in the attachment of gripper (point M) and m_A at the point A of rotary base (Fig. 2) [9].

Then the system of differential equations describing the motion of the manipulator with ties (1), obtained by using the Lagrange equations with undetermined multipliers [10], can be written in the following form

$$
\begin{gathered}
\dot{x}_1 = x_2, \\
\dot{x}_2 = F_1 \frac{x_1}{ml_1} + F_2 \frac{x_1 - x_B}{ml_2} + F_3 \frac{x_1 + x_B}{ml_3}, \\
\dot{x}_3 = x_4, \\
\dot{x}_4 = F_1 \frac{x_3 + O_1A \cdot \sin x_7 - y_B}{ml_1} + F_2 \frac{x_3 - y_B}{ml_2} + F_3 \frac{x_3 - y_B}{ml_3}, \\
\dot{x}_5 = x_6, \\
\dot{x}_6 = F_1 \frac{x_5 - O_1A \cdot \cos x_7}{ml_1} + F_2 \frac{x_5}{ml_2} + F_3 \frac{x_5}{ml_3} - g, \\
\dot{x}_7 = x_8, \\
\dot{x}_8 = F_1 \frac{(x_3 - y_B) \cdot \cos x_7 + x_5 \cdot \sin x_7}{O_1A \cdot m_A l_1} + F_4 \frac{z_D \cdot \sin x_7 - y_B \cdot \cos x_7}{O_1A \cdot m_A l_4} + \frac{g}{O_1A} \sin x_7,
\end{gathered}
\tag{3}
$$

Where $x_1 = x$, $x_3 = y$, $x_5 = z$, $x_7 = \varphi$; $F_k, k = 1 \div 4$ - forces in the links of the manipulator.

5 The Task of Positioning

The common task of moving executive element (gripping arm) is divided into three stages - the positioning of the grip provided by the geometry of the mechanism, synthesis of its trajectory in the work area space and the definition of motion law on the obtained trajectory.

The positioning of manipulator's grip during technological operations consists of moving it from the initial state, which is defined by the coordinates of the point $M_0(x_{M0}, y_{M0}, z_{M0})$, to end position $M_k(x_{Mk}, y_{Mk}, z_{Mk})$.Moreover, from the initial configuration of the manipulator, defined by generalized coordinatesl_{i0}, we need to find target configuration l_{ik}. As the number of generalized coordinates of the manipulator, equal to four, exceeds the number of generalized coordinates of grip, equal to three, thus target end position of the object meets a variety of system configurations.

The task of positioning is solved in [11] from the condition of minimal change of the lengths of the control electro-cylinders. The links lengths $l_{2k}(x_{Mk}, y_{Mk}, z_{Mk})$, $l_{3k}(x_{Mk}, y_{Mk}, z_{Mk})$ are determined uniquely from the system of equations (1) and the links lengths $l_{1k}(x_{Mk}, y_{Mk}, z_{Mk})$, $l_{4k}(x_{Mk}, y_{Mk}, z_{Mk})$ are found from the condition of a quadratic function minimum

$$\Phi(\varphi) = (l_{1k} - l_{10})^2 + (l_{4k} - l_{40})^2, \tag{4}$$

The lengths of the executive links are imposed by the structural limitations in a form of inequalities $l_{1\min} \le l_1 \le l_{1\max}$, $l_{4\min} \le l_4 \le l_{4\max}$.

Achieving the optimal solution is provided by the necessary conditions for the stationarity of the function (4) [12]. Thus, there is a final configuration of the manipulator defined by the lengths of the executive links of the manipulator l_{ik}.

The design procedure of a programmable movement of the manipulator-tripod working body from the initial to the end state when the motion is occurred according to a sinus law of the actuating link rod's acceleration changing and when motion occurs along a straight line was developed.

Specifying the law of motion of the links from l_{i0} to l_{ik} at time T on the basis of "soft" start and touch, conditioned by zero velocity and acceleration of the gripper in the initial and final positions

$$l_i(t) = l_{i0} + (l_{ik} - l_{i0}) \cdot \left[\frac{t}{T} - \frac{1}{2\pi} \sin\left(\frac{2\pi t}{T} \right) \right], \tag{5}$$

then the parametric equations of the gripper arm trajectory are determined from the solution of the inverse kinematic problem.

The trajectory, optimal on a gripper's time of movement, is a straight line. However, such displacement is possible in a case when all points of the segment M_0M_k belongs to the set, which is part of the service area. The dependencies of coordinates x_M, y_M, z_M on the length of a trajectory are determined from the equation of the straight line in space passing through two points M_0 and M_k. The law of motion along the straight line M_0M_k also has been taken so that it satisfies the requirements of «soft» touch. Thus, the laws of links' lengths changing $l_i(t)$ are derived from the equations without the solving the inverse kinematic problem [13].

When implementing a linear trajectory, such end point positioning of the manipulator gripper are possible, for which the linear velocity of the rod ends of links 1, 2 and 3 change sign, i.e. they perform reciprocating motion in relative motion. So Fig. 4 shows that the motion of the gripper of the manipulator along a straight line M_0M_1, the linear velocity of the rod ends of links 2 and 3 change the sign. The condition under which the linear velocity of the rod ends of links 2 and (or) 3 is always greater than zero, is the inequality $\beta \geq \pi/2$ and (or) $\gamma \geq \pi/2$. β and γ are the angles between the axes of the respective links and the trajectory of a point M. For example, at the gripper motion along a straight line M_0M_2 (Fig. 4) the constancy of the signs of the linear velocities of the rods of these links is observed, as in this case, the angles β and γ between the axes of the links 2 and 3 and direct line M_0M_2 is more than $\pi/2$. The linear velocities of the rod ends of links 2 and 3 are negative in the case when these angles are less than $\pi/2$, and, simultaneously, the length of the trajectory of grip transfer point, does not exceed $M_0M_k \leq l_2(T)\cos\beta$ for link 2, and $M_0M_k \leq l_3(T)\cos\gamma$ for level 3. Thus, to derive analytical conditions for the constancy of the sign of the linear velocities of the rods of the links 2 and 3, it is necessary to solve the problem of computing the angles β and γ between the straight lines passing through the axes of the links 2 and 3 and straight line M_0M_k.

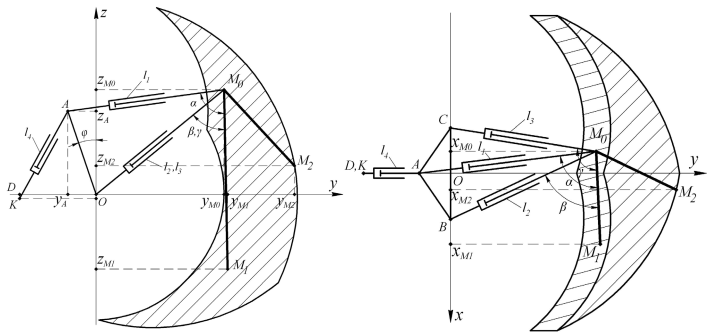

Fig. 4. To the determination of the sign of the linear velocity of links

The equation of the line passing through the points B and M_0 (the axis of link 2) has the form

$$\frac{x - OB}{x_{M0} - OB} = \frac{y}{y_{M0}} = \frac{z}{z_{M0}}, \tag{6}$$

and passing through the point C and M_0 (the axis of link 2)

$$\frac{x+OB}{x_{M0}+OB}=\frac{y}{y_{M0}}=\frac{z}{z_{M0}}. \tag{7}$$

The values of the angles β and γ between the axes of the links 2 and 3 and straight line M_0M_k equal to the angles between their respective guide vectors.

$$\beta=\arccos\left[\pm\frac{(x_{M0}-OB)(x_{Mk}-x_{M0})+y_{M0}(y_{Mk}-y_{M0})+z_{M0}(z_{Mk}-z_{M0})}{\sqrt{(x_{M0}-OB)^2+(y_{M0})^2+(z_{M0})^2}\cdot\sqrt{(x_{Mk}-x_{M0})^2+(y_{Mk}-y_{M0})^2+(z_{Mk}-z_{M0})^2}}\right], \tag{8}$$

$$\gamma=\arccos\left[\pm\frac{(x_{M0}+OB)(x_{Mk}-x_{M0})+y_{M0}(y_{Mk}-y_{M0})+z_{M0}(z_{Mk}-z_{M0})}{\sqrt{(x_{M0}+OB)^2+(y_{M0})^2+(z_{M0})^2}\cdot\sqrt{(x_{Mk}-x_{M0})^2+(y_{Mk}-y_{M0})^2+(z_{Mk}-z_{M0})^2}}\right]. \tag{9}$$

The condition under which the linear velocity of the link rod 1 (Fig. 5) does not change the sign has the form

$$V_M^{/}-V_A^{/}\geq 0, \tag{10}$$

where the projection of the velocities of the points M and A on the axis of link 1 are of the form

$$V_M^{/}=V_M\cdot\cos\alpha=\sqrt{\left(\frac{dx_M}{dt}\right)^2+\left(\frac{dy_M}{dt}\right)^2+\left(\frac{dz_M}{dt}\right)^2}\cdot\cos\alpha. \tag{11}$$

$$V_A^{/}=V_A\cdot\cos\delta=\frac{d\varphi}{dt}\cdot OA\cdot\cos\delta, \tag{12}$$

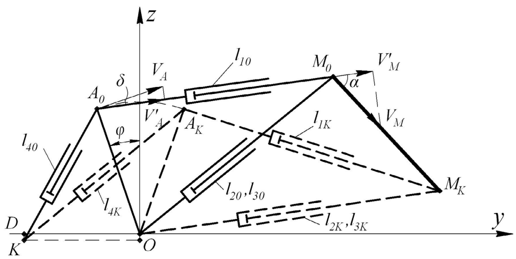

Fig. 5. To the determination of the sign of the linear velocity of link 1

The values of the angles α and δ are defined as the angles between two straight lines in space AM_0, M_0M_k и AM_0, respectively.

6 Trajectory Synthesis

The system of differential equations describing the motion of a manipulator with holonomic links is recorded using the Lagrange equations with undetermined multipliers [14].

Enter symbols $x_1 = X$, $x_3 = Y$, $x_5 = Z$, $x_7 = \varphi$, $F_k, k = 1,2,3,4$ - control efforts in the manipulator links. Functions that transfer manipulator gripper from the initial to the end position during the time *T*, are found from the condition of functional minimum

$$J = \Phi\left(x_7(T)\right) + \frac{1}{2}\int_0^T \left[\dot{x}_2^2 + \dot{x}_4^2 + \dot{x}_6^2 + O_1A^2 \cdot \dot{x}_8^2\right] dt. \tag{13}$$

Desired functions must satisfy the following boundary conditions: $x_{2S-1}(0) = x_{2S-1,0}, x_{2S-1}(T) = x_{2S-1,T}, x_{2S}(0) = x_{2S}(T) = 0$. The value of the function $x_7(T)$ is unknown. Writing down the required stationary conditions [13] for $x_k(t)$, k=1, 3, 5, taking into account the boundary conditions, we obtain:

$$x_k(t) = \frac{-2\left[x_k(T) - x_k(0)\right]}{T^3} t^3 + \frac{3\left[x_k(T) - x_k(0)\right]}{T^2} t^2 + x_k(0). \tag{14}$$

According to [15] the boundary condition for the influence function

$$\lambda_7(T) = \frac{\partial \Phi\left[(x_7(T)\right]}{\partial x_7(T)}, \quad \Phi(x_7(T)) = -\frac{\mu x_7^2(T)}{2T^3}, \tag{15}$$

where μ is a constant factor, which is determined by the results of the obtained solution analysis and can be adjusted at the design stage. Since the solution of a variational problem.

$$\dddot{x}_7(T) = const = \dddot{x}_7(t) = \frac{x_7(T)}{T^3}, \tag{16}$$

so after integration we get

$$\varphi(t) = \frac{\mu\varphi(T)}{6T^3} t^3 - \frac{\mu\varphi(T)}{4T^2} t^2 + \varphi(0) \cdot \tag{17}$$

Then at t=T we define an unknown base rotation angle in a final moment of time x_7=$\varphi \cdot O_1A$, and from the equations (2) we find the laws of change of manipulator links' lengths l_k=(t).

Programmatic forces, needed to implement the synthesized motion laws of the manipulator links by the control system, are found from the solution of the equations of dynamics.

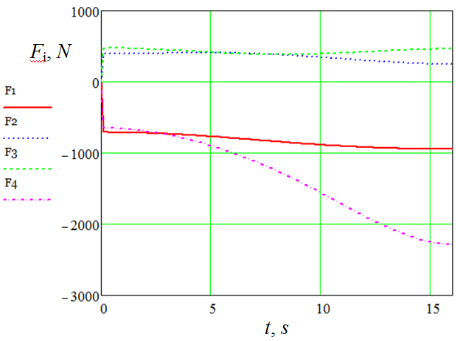

Fig. 6. The dependences of efforts in executive links of the manipulator

7 Handling of the Manipulator-Tripod

For implementation of the robot programmatic motion laws we build a control system with feedback by position, which solve the problem of the contouring control [16, 17].

Block diagram of the control system developed for mobile robot manipulators drives is shown in Fig. 7.

A linear DC motor - actuator plays as an operating mechanism of a manipulator link. In the developed device the "SKF group" actuators CAHB-21 series are used. These motors do not have an internal control system, but they are equipped with the feedback sensor to determine the current status of the device. Feedback is implemented in the form of linear potentiometer, reflecting the absolute value of the rod position. Signal of tracking feedback U_{fb} (Fig. 7) feed to the input of the analog-digital converter (ADC) of drives control unit (DCU). The rated voltage of the actuator drive is 24V. The speed of the rod is regulated by changing the control PWM signal.

The control system completely governs the mechanisms of the system having 4 managed degree of freedom of the manipulator-tripod and the rotary platform, on which the manipulator is placed. DCU is based on 32-bit microcontroller family STM32F407 with ARM Cortex-M4Farchitecture. The high clock speed and a considerable amount of internal memory provide necessary computing resources to meet the managing challenges. In addition, the controller has a wide range of peripheral devices, ADC and controllers of USB 2.0, Ethernet, RS-232, CAN interfaces.

Microchip of a bridge amplifier is included in the control loop of PWM signals generated by built-in timers of microcontroller. The amplifier functions are performed by dual full H-bridge on the chip VNH3SP30passing maximum current of up to 30A for

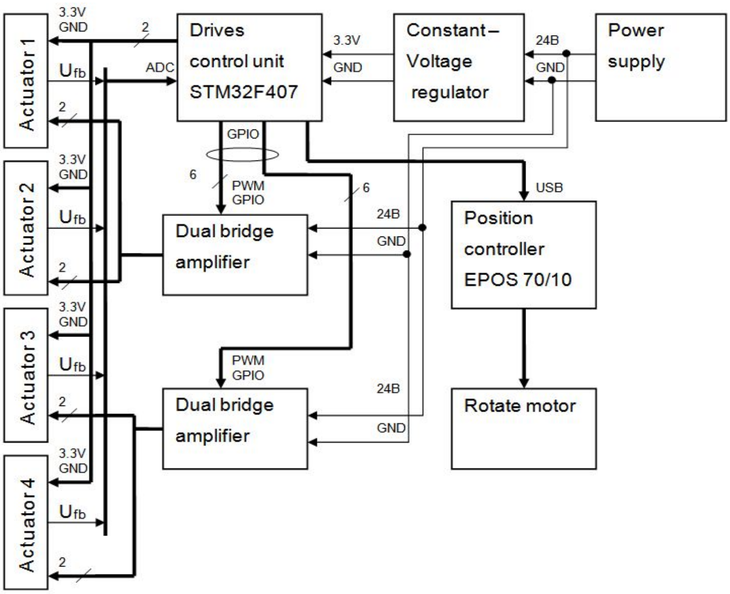

Fig. 7. Block diagram of the manipulator drives control system

each channel. Reversal of the motor rotation (direction of the rod movement) is set by the control signals on the GPIO pins of the controller. As a rotation drive of the rotary base of the manipulator the "Maxon motors"servo motors RTG 060-100 are used. Position controller EPOS 70/10 governs the servo motor. Executive instructions from the host controller STM32F407 are transferred to the position controller via USB.

You can wirelessly control this robot from a remote computer. Connectivity is provided by WiFi module, connected to one of the USB ports of on-board controller. The system of remote motion control is implemented on the base of personal computer. Its aim is to calculate in real time a coordinated movement of all actuators on the base of a given mathematical model, issuing control commands for DCU and feedback data processing.

8 Results of Numerical and Experimental Modeling

Numerical and experimental simulation was conducted for the manipulator with the following parameters: the initial length of link 1 is 1160 mm, stroke 610 mm, initial length of the 2nd and 3rd links is 1140 mm, stroke 610 mm, the initial length of 4-th level is 843 mm, and the stroke of 457 mm. Maximum pushing and retracting load is 2300 N. Speed at full load 45 mm/s, at no load 65 mm/s. As a result of solving the problem of identification [4] for the developed robot is obtained m=50 kg, m_A=60 kg. Mass of carried load is m_G=15 kg.

The initial values of the lengths of the manipulator links are equal to l_{10}=1400 mm, l_{20}=1500 mm, l_{30}=1352 mm, l_{40}=903 mm. Those values obtained by reading the position sensors correspond to the coordinates of the gripper $x(0)$=-297 mm, $y(0)$=1117 mm, $z(0)$=759 mm, and the angle of inclination of the manipulator base is $\varphi(0)$=0,323 rad. Having finite values of the coordinates of gripper: $x(T)$=300 mm, $y(T)$=1500 mm, $z(T)$=-700 mm (Fig. 8), the laws (7) of gripper coordinates change $x_k(t)$ and the angle of inclination of the manipulator rotary base φ(t) are defined, and by the expressions (1) - the lengths of the links.

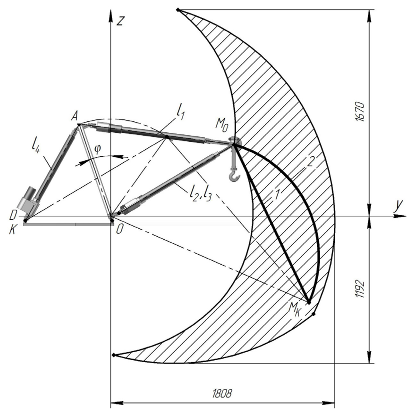

Fig. 8. Moving the gripper along a straight line (1) and an a priori unknown trajectories for a sinusoidal law of acceleration change (2)

Fig. 9 shows software and experimental laws of the executive link's lengths change to move the gripper with the starting coordinates $M_0(x_{M0}, y_{M0}, z_{M0})$ and ending coordinates $M_k(x_k, y_k, z_k)$ for the time T=7,1 s according to the laws (7) of the gripper point coordinates change.

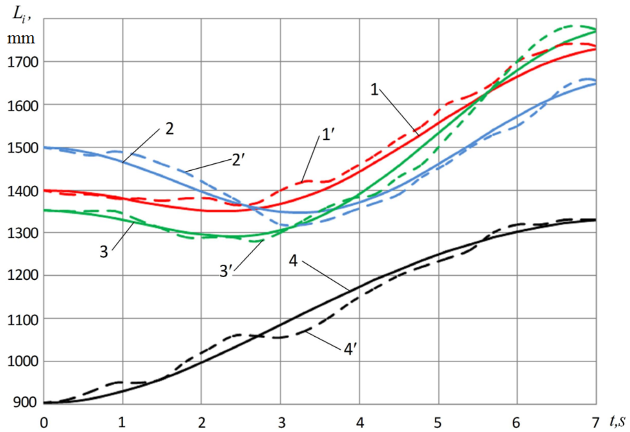

Fig. 9. Calculated (curves 1-4) and experimental (curves 1'-4') time dependencies for the manipulator link's lengths 1 to 4 changes when the gripper moves straight

9 Conclusion

Presented calculated and experimental dependencies of a change of manipulator links lengths on the time during the gripper motion along a straight line and at a priori unknown path for sinusoidal law of acceleration change have demonstrated, subject to the measurement errors, theoretical and experimental results match, that may serve as a proof of feasibility of the examined motion laws. From Fig. 9 it is clear that when implementing the straight-line trajectory linear velocity of 1, 2 and 3 link's rods change the sign, i.e. they make reciprocating motion in relative motion. Moreover, despite the more length of the trajectory of gripper with sinusoidal law of change of acceleration of the executive links, the total relative movement of rods in the implementation of the straight-line trajectory exceeds the corresponding relative displacements of the rods under the sinusoidal law of change of acceleration of the executive links (Fig. 8). Under the sinusoidal law of change of acceleration of the executive link's rods, their lengths at positioning the gripper change monotonically, and the trajectory of gripper is always in service zone of the manipulator, while the straight-line trajectory of the gripper is feasible not for any location of the endpoint positioning. Thus, it can be argued that the algorithm and control system of a manipulatorgripper transfer under the sinusoidal law of changes of its executive links are preferable.

Acknowledgement. This work was supported by the Russian Foundation for Basic Research (project 15-01-04577-a and project 13-08-00387-a).

References

1. Glazunov, V.A., Kaliski, A.W., Krainev, A.F.: Spatial mechanisms of parallel structures, p. 95. Nauka, M. (1991) (in Russian)
2. The handling robot Festo [Electronic resource]. https://www.festo.com/cat/ru-uk_ua/products_EXPT
3. The handling robot FlexPicker IRB 360 company AAB www.abb.com/robotics [Electronic resource]. http://www.roboticturnkeysolutions.com/robots/abb/datasheet/IRB_360.pdf
4. OKUMA PM-600 Vertical Machining Centers [Electronic resource]: Verticalnye machining centers. http://www.okuma.com/pm-600
5. Olazagoitia, J.L., Wyatt, S.: New PKM Tricept T9000 and its application to flexible manufacturing at Aerospace Industry / SAE International, Paper (2007)
6. Korendesev, A.I., Salamandra, B.L., Tyves, L.I., et al.: Manipulyatsionnye sistemy robotov (Manipulation Systems for Robots). Mashinostroenie, Moscow (1989) (in Russian)
7. Gerasun, V.M., Zhoga, V.V., Nesmiyanov, I.A., Skakunov, V.N., Eremenko, A.V., Fedchenkov, P.V., Dyashkin-Titov, V.V.: RF Patent 2476372 IPC7 B66C23/36, Byull. Izobret. (2013) (in Rusaian)
8. Gerasun, V.M., Zhoga, V.V., Nesmiyanov, I.A., Vorob'eva, N.S., Dyashkin-Titov, V.V.: The way to describe operative range of mobile manipulating tripod. Mashinostr. Inzh. Obraz. (3), 2–8 (2013)
9. Zhoga, V.V., Gerasun, V.M., Nesmiyanov, I.A., Vorob'eva, N.S., Dyashkin-Titov, V.V.: Synthesis of optimal dynamic motion of the manipulator-tripod. Published in Problemy Mashinostroeniya i Nadezhnosti Mashin (2), 85–92 (2015) (in Russian)
10. Butenin, N.V.: Introduction to analytical mechanics. Nauka. Gl. red. fiz._mat. lit, Moscow (1971) (in Russian)
11. Gerasun, V.M., Zhoga, V.V., Nesmiyanov, I.A., Vorob'eva, N.S., Dyashkin-Titov, V.V.: Optimal configurations of manipulating tripod with rotating bed. Mekhatron., Avtomatiz., Upr. (6), 16–21 (2013)
12. Kolovskii, M.Z., Sloushch, A.V.: Osnovy dinamiki promyshlennykh robotov (Foundations of Industrial Robot Dynamics). Nauka. Gl. red. fiz._mat. lit, Moscow (1998) (in Russian)
13. Gerasun, V.M., Zhoga, V.V., Nesmiyanov, I.A., Vorob'eva, N.S., Dyashkin_Titov, V.V.: The way to synthesize a program for manipulator motions based on spatial mechanism of parallel structure with four translatory pairs. In: 5_ya Rossiiskaya mul'tikonferentsiya po problemam upravleniya. Materialy konf. Upravlenie v tekhnicheskikh, ergaticheskikh, organizatsionnykh i setevykh sistemakh (UTEOSS_2012) (Proc. 5th Russian Multi-Conf. on Control Problems "Control in Engineering, Energy, Managing and Network Systems (UTEOSS-2012)), St. Petersburg, pp. 722–725 (2012)
14. Zhoga, V., Gavrilov, A., Gerasun, V., Nesmianov, I., Pavlovsky, V., Skakunov, V., Bogatyrev, V., Golubev, D., Dyashkin-Titov, V., Vorobieva, N.: Walking Mobile Robot with Manipulator-Tripod. In: Proceedings of Romansy 2014 XX CISM-IFToMM Symposium on Theory and Practice of Robots and Manipulators. Mechanisms and Machine Science, vol. 22, pp. 463–471. Springer International Publishing Switzerland (2014)
15. Bryson, A.E., Ho, Y.: Applied Optimal Control. Hemisphere/Wiley (1975)

16. Gerasun, V.M., Nesmiyanov, I.A.: Manipulator control systems based on spatial slave mechanisms. Mekhatron., Avtomatiz. Upr. (2), 24–28 (2010) (in Russian)
17. Nesmianov, I., Zhoga, V., Pavlovski, V., Vorobieva, N.: The control system of the manipulator agricultural robot. Izvestiya Nizhnevolzhskogo agrouniversitetskogo kompleksa: Nauka i vyisshee professionalnoe obrazovanie 35(3), 226–231 (2014) (in Russian)