

$$q_1(t) = \frac{1}{2} \text{ArcCos} \left[\frac{Py(t)^2 - Px(t)^2}{Px(t)^2 + Py(t)^2} \right],$$

$$q_2(t) = \text{ArcTan} \left[\frac{a_3^2 P_{za} + a_3 P_{za} (-a_6^2 + P_{xy}^2 + P_{za}^2)}{a_3^2 (P_{xy}^2 + P_{za}^2)} \right]$$

$$\left[\frac{-a_3^2 P_{xy}^2 (a_3^4 + (-a_6^2 + P_{xy}^2 + P_{za}^2)^2 - 2a_3^2 (a_6^2 + P_{xy}^2 + P_{za}^2))}{a_3^2 (P_{xy}^2 + P_{za}^2)} \right]$$

$$q_3(t) = -\text{ArcTan} \left[\frac{1}{a_3^2 a_6 (P_{xy}^2 + P_{za}^2)^2} (a_3^5 (P_{xy}^2 - P_{za}^2) + a_3 a_6^2 (a_6^2 - P_{xy}^2 - P_{za}^2) (P_{xy}^2 - P_{za}^2) - a_3^3 (P_{xy}^2 - P_{za}^2) (2a_6^2 + P_{xy}^2 + P_{za}^2) + 2(a_3^2 - a_6^2)) \right]$$

$$P_{za} \sqrt{-a_3^2 P_{xy}^2 (a_3^4 + (-a_6^2 + P_{xy}^2 + P_{za}^2)^2 - 2a_3^2 (a_6^2 + P_{xy}^2 + P_{za}^2))}$$

$$a_6 = a_4 + a_5 + \frac{t^2 Q_5}{i_5^2 m_5 + i_6^2 m_6}, P_{za} = Pz(t) - a_1 - a_2,$$

$$P_{xy} = Px(t)^2 + Py(t)^2$$

Analytical solution for $q_4(t), q_5(t), q_6(t)$ obtained from the dynamic matrix equations of Lagrange [13-15].

$$q_4(t) = \frac{t^2 Q_4}{i_4^2 m_4 + i_5^2 m_5 + i_6^2 m_6}, q_5(t) = \frac{t^2 Q_5}{i_5^2 m_5 + i_6^2 m_6}, q_6(t) = \frac{t^2 Q_6}{i_6^2 m_6}.$$

Here Q_k are the generalized forces created by the link drives, m_k is the mass of the link, i_k is the radius of inertia of the link.

Thus, the functions of the generalized coordinates of the gripper of the manipulator are determined for the movement of the gripper along the optimal trajectory with bypassing the obstacle.

The presented ABI hybrid method allows you to build the optimal trajectory of the manipulator when avoiding obstacles and to control the movement along the trajectory.

IV. CONCLUSION

In this paper, we consider the urgent task of constructing an optimal spatial trajectory of the grip movement relative to the fixed base of the manipulator strut, taking into account the obstacle bypass.

As a result of the hybrid method, the optimal path of manipulator grip motion is obtained, which ensures continuity and smoothness of grip motion. Minimizing the length of the path while bypassing the obstacle reduces the operating stroke time of the manipulator. Unlike the works considered, the hybrid method is multi-step and combines finite-element grid model construction methods, graph shortest path determination methods, interpolation, approximation, and matrix methods. The combination of these methods allows solving the problem of determining the optimal trajectory when bypassing the obstacle by the manipulator capture in the assumption of uniform movement of the capture on the main working section.

A theorem is presented that determines the relationship between the length of time the manipulator grip moves in equally accelerated and equally slow sections. The theorem is used for the subsequent optimization of the manipulator travel time in sections.

A new hybrid ABI method for constructing the optimal trajectory of the manipulator's grip taking into account obstacle avoidance is introduced. The ABI hybrid method has six main steps. The method combines a finite element mesh approach, a graph model construction method, A * method for finding the minimum path for a graph, a B-spline interpolation method, polynomial approximation, and a matrix method. The combination of grid, graph, interpolation and matrix methods allows you to completely solve the problem.

REFERENCES

- [1] Reiter, A., Müller, A., & Gattringer, H. "On Higher Order Inverse Kinematics Methods in Time-Optimal Trajectory Planning for Kinematically Redundant Manipulators", *Transactions on Industrial Informatics*, IEEE, vol. 14(4), 2018 pp. 1681-1690.
- [2] Beiki, M. R. E., & Irani-Rahaghi, M. "Optimal Trajectory Planning of a Six DOF Parallel Stewart Manipulator", *6th RSI International Conference on Robotics and Mechatronics (IcRoM)*, IEEE, Oct. 2018, pp. 120-125.
- [3] Xidias, E. K. "Time-optimal trajectory planning for hyper-redundant manipulators in 3D workspaces" *Robotics and computer-integrated manufacturing*, 50, 2018, pp. 286-298.
- [4] Wang, M., Luo, J., Fang, J., & Yuan, J. "Optimal trajectory planning of free-floating space manipulator using differential evolution algorithm", *Advances in Space Research*, vol. 61(6), 2018, pp. 1525-1536.
- [5] Diao, S., Chen, X., Wu, L., Zhong, Z., & Lin, Z. "Task-level time-optimal collision avoidance trajectory planning for grinding manipulators", *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 233(8), 2019, pp. 2894-2908.
- [6] Huang, J., Hu, P., Wu, K., & Zeng, M. "Optimal time-jerk trajectory planning for industrial robots", *Mechanism and Machine Theory*, vol. 121, 2018, pp. 530-544.
- [7] Geng, J., & Arakelian, V. "Design of Partially Balanced Planar 5R Symmetrical Parallel Manipulators via an Optimal Motion Planning" *In IFTOMM World Congress on Mechanism and Machine Science*. Springer, Cham, Jun. 2019 pp. 2211-2220
- [8] Kabir, A. M., Shah, B. C., & Gupta, S. K. "Trajectory planning for manipulators operating in confined workspaces" *In 2018 IEEE 14th International Conference on Automation Science and Engineering (CASE)*, IEEE, Aug. 2018. pp. 84-91
- [9] Kumar, V., Sen, S., Shome, S. N., & Roy, S. S. "An Approach to Trajectory Planning for Underwater Redundant Manipulator Considering Hydrodynamic Effects" *In Machines, Mechanism and Robotics*. Springer, Singapore, 2019, pp. 377-388
- [10] Hu, J., Sun, Y., Li, G., Jiang, G., Kong, J., Xiong, H. & Jiang, D. "Trajectory planning algorithm and simulation of 6-DOF manipulator", *International Journal of Wireless and Mobile Computing*, vol. 14(2), 2018, pp. 138-148.
- [11] Chettibi, T. "Smooth point-to-point trajectory planning for robot manipulators by using radial basis functions". *Robotica*, vol. 37(3), 2019, pp. 539-559.
- [12] E. I. Vorobyov, S. A. Popov, G. I. Sheveleva, *Mechanics of industrial robots: in 3 books, Part 1: Kinematics and dynamics*, M.: Higher. school, 1988, p. 304.
- [13] G. I. Melnikov, S. E. Ivanov, V. G. Melnikov, "The modified Poincare-Dulac method in analysis of autooscillations of nonlinear mechanical systems", *Journal of Physics: Conference Series*, vol. 570(2), IOP Publishing, 2014, p.022002.
- [14] T. V. Zudilova, S. E. Ivanov, L. N. Ivanova, "The automation of electromechanical lift for disabled people with control from a mobile device", *Computing Conference*, IEEE, 2017, pp. 668-674.
- [15] G. I. Melnikov, N. A. Dudarenko, K. S. Malykh, L.N. Ivanova, V. G. Melnikov, "Mathematical models of nonlinear oscillations of mechanical systems with several degrees of freedom", *Nonlinear Dynamics and Systems Theory*, vol. 17(4), 2017, pp. 369-375.