Implementation and Computer Simulation of Robot Joint Error Maximum Mutual Compensation

YAUHENI VERYHA, JERZY KUREK
Department of Mechatronics
Warsaw University of Technology
Chodkiewicza Str. 8, 02-525, Warsaw
POLAND

Abstract: The method of end-effector pose accuracy improvement using joint error mutual compensation for robotic manipulators with rotation joints was presented. The computer simulation and experiments of the developed method showed that it was possible to perform the technological operations with a higher accuracy in the special areas of the robot working space using the developed approach. The method provides the basis for an industrial application of joint error mutual compensation in the conventional robotic manipulators. The practical areas and typical robotic systems where the developed framework of joint error mutual compensation could be applied were presented.

Key-Words: error compensation, robotic manipulator, robotic system, error compensation, pose accuracy, computer simulation.

1 Introduction

Robot end-effector pose accuracy improvement is the subject of many research papers in the area of robotics. A number of performed experiments showed significant dependence of robot pose accuracy on robot end-effector location in the robot working space [1, 4]. This allows locating special robot configurations and, thus, special areas in robot working space with the highest robot end-effector accuracy. It is assumed that high-precision technological operations should be performed in these areas with the highest end-effector pose accuracy.

Smolnikov [5] proposed the theoretical basis for the investigation of end-effector pose accuracy of robotic manipulators with rotational joints. He showed the geometrical dependence of the end-effector pose accuracy on joint error values. Dimov et al [1] presented the experimental results of measuring end-effector pose accuracy and end-effector pose repeatability of 2-R robotic manipulator. The results showed a significant dependence of the end-effector pose accuracy and end-effector pose repeatability on the position of the working point in the robot working space. A number of experimental results confirmed the dependence of end-effector pose accuracy on the parameters of the trajectory. Kieffer et al [4] presented some experimental and theoretical results that defined the dependence of the end-effector path and pose accuracy on the parameters of the end-effector trajectory.

The main goals of the presented research were to develop the method for robotic manipulator pose accuracy improvement based on the joint error maximum mutual compensation and perform the computer simulation of 2-R and 6-DOF robotic manipulator end-effector positioning to confirm the theory.

2 Method of Robot Joint Error Maximum Mutual Compensation

When the robot performs, for example, the welding operation in the manufacturing cell, it is important to use different parts of the robot working space. In some cases, it is possible to change the location of the working point at some value [2]. This slight change of the end-effector working position allows performing local optimization of the end-effector pose accuracy by using robot joint error mutual compensation. For the kinematic scheme of 2-R robotic manipulator, shown in Fig. 1, elementary end-effector Cartesian errors Δx and Δy in the base coordinate system can be defined as:

$$\begin{aligned}\Delta x &= -(l_1 \sin q_1 + l_2 \sin(q_1+q_2))\Delta q_1 - l_2 \sin(q_1+q_2)\Delta q_2 \\ \Delta y &= (l_1 \cos q_1 + l_2 \cos(q_1+q_2))\Delta q_1 + l_2 \cos(q_1+q_2)\Delta q_2,\end{aligned} \tag{1}$$

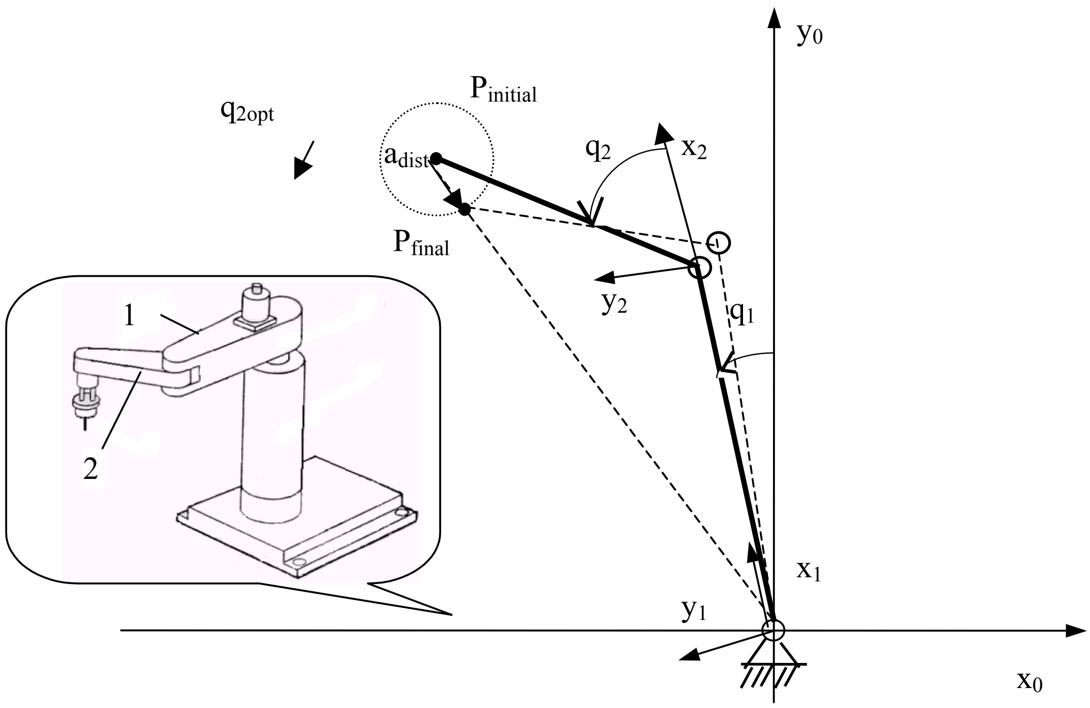

Fig. 1. The kinematic scheme of 2-R robotic manipulator and local optimization of robot end-effector pose accuracy

where q_1 and q_2 joint coordinates, Δq_1 and Δq_2 elementary joint errors of the first and second joints, l_1 and l_2, accordingly, lengths of the first and second manipulator links, x_0y_0 – base robot coordinate system, x_1y_1 and x_2y_2, accordingly, the Cartesian coordinate systems of first and second links, q_1 and q_2 first and second robot joint coordinates.

The square of the Cartesian coordinate end-effector error ΔL^2 ($\Delta L^2 = \Delta x^2 + \Delta y^2$) using (1), can be defined as:

$$\Delta L^2 = l_2^2\,\Delta q_2^2 + 2\Delta q_1\,\Delta q_2\,l_2^2 + \Delta q_1^2(l_1^2 + l_2^2) + \\ + 2\,l_1 l_2(\Delta q_1^2 + \Delta q_1\Delta q_2)\cos q_2\,, \quad (2)$$

The maximum end-effector pose accuracy can be obtained if $\Delta L^2 = 0$ in (2). In this case, the optimal joint coordinate q_{2opt} can be found, for which the joint errors Δq_1 and Δq_2 could be maximally or fully compensated. Thus, robot joint error maximum mutual compensation can be obtained. To find the optimal joint coordinate q_{2opt} from (2), the analytical solution can be defined for 2-R robotic manipulator as:

$$q_{2opt} = \arccos\left(-\frac{l_2^2\Delta q_2^2 + 2\Delta q_1\ \Delta q_2 l_2^2 + \Delta q_1^2(l_1^2 + l_2^2)}{2l_1 l_2(\Delta q_1\ \Delta q_2)}\right), \quad (3)$$

The dependence of the end-effector positioning accuracy of 2-R robotic manipulator with the link lengths of $l_1 = 0.4$ m and $l_2 = 0.25$ m and permanent joint errors $\Delta q_1 = 2.29 \times 10^{-6}$ and $\Delta q_2 = 2.11 \times 10^{-6}$ rad, based on (3), is shown in Fig. 2.

In practice, equation (3) does not allow reaching joint error maximum compensation, because joint errors Δq_1 and Δq_2 will change with the change of the locaion of the working point [3, 6]. Experimental results from [4] allows making a conclusion that average values of joint errors Δq_1 and Δq_2 will be the same only for similar trajectories in the given area of the robot working space.

In order to improve robot end-effector pose accuracy ΔL based on (3), the following method was developed. The developed optimization method flow-diagram is shown in Fig. 3. One should move the given initial working point $P_{initial}$, as it is shown in Fig. 1, in the closest direction to the joint coordinate q_{2opt} found from (3). This will change the initial working point $P_{initial}$ into the point P_{final} at which the average values of joint errors should not change significantly (more than 1%) [4]. Similarly, the optimization of the end-effector pose accuracy in the given working points can be performed for other types of robots.

As an example, one can consider the allowed change $a_{dist} = 10$ mm of the working point $P_{initial}$ (see Fig. 2). According to (3), the change of $P_{initial}$ location should be done in such a way, that the joint coordinate q_2 could be as much close as possible to the q_{2opt} (see Fig.1).

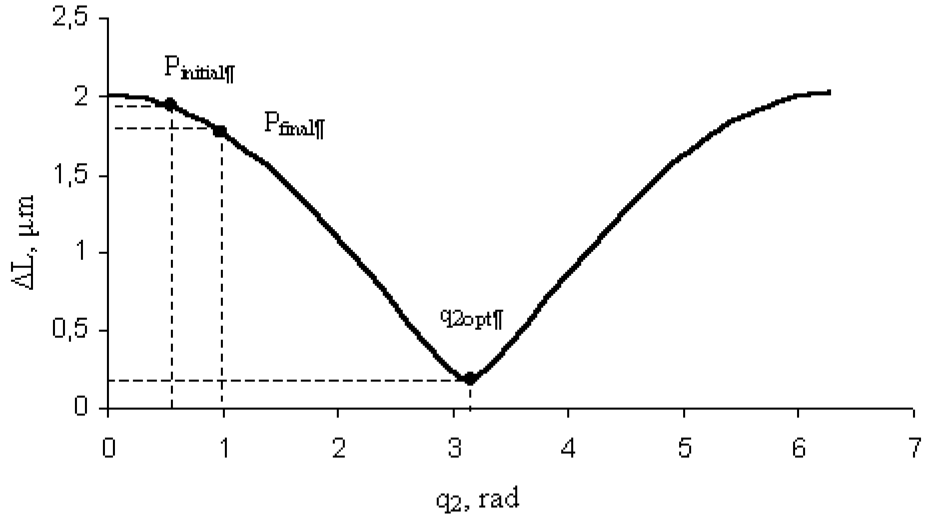

Fig. 2. Graph of dependence of robot end-effector positioning accuracy ΔL on the distance from the optimal joint coordinate q_{2opt}

In this case, the larger joint error compensation will take place in the new point P_{final}, as it follows from (3). This will lead to an improvement of the end-effector pose accuracy ΔL when performing the given technological operation. It is supposed that a given technological operation must be performed in point $P_{initial}$ with Cartesian coordinates x = -288.053 mm and y = 529.429 mm, joint coordinates q_1 = 1.77 rad and q_1 = 0.79 rad (see Fig. 1) by the 2-R robotic manipulator. Based on the presented experimental results, the end-effector positioning accuracy was ΔL = 1.9 μm in the point $P_{initial}$. The joint error values $\Delta q_1 = 2.29 \times 10^{-6}$ rad and $\Delta q_2 = 2.11 \times 10^{-6}$ rad were found in the point $P_{initial}$ based on the manipulator kinematic model. Using the equation (3), the optimal value of the joint coordinate q_{2opt} = 3.147 rad was found for the given conditions. According to the previous discussions, the value of the initial joint coordinate q_2 = 0.79 rad in the point $P_{initial}$ should be increased at some value to become closer to the optimal value q_{2opt} = 3.147 rad. Assuming that the allowed distance from the $P_{initial}$ to P_{final} is 10 mm, one can increase the second joint coordinate q_2 by 0.08 rad. The rotation value α = 0.08 rad was found based on the assumption that the rotation of the second link with the length of 0.25 m on the angle 0.08 rad would not exceed the maximum allowed value of a_{dist} = 10 mm from the initial position of the point $P_{initial}$. After the rotation on the allowed angle of 0.08 rad in the closest direction to the q_{2opt}, the new joint coordinates of the point P_{final} were q_1 = 1.77 rad and q_2 = 0.87 rad. Taking into account that the old values of the joint errors did not change more than 1% [4], one can use the old values of the average joint errors Δq_1 and Δq_2 in order to determine the end-effector positioning accuracy. Using (1), the new value of robot end-effector positioning accuracy ΔL = 1.78 μm was found. The comparison of the new end-effector pose accuracy ΔL = 1.78 μm in the point P_{final} with the old one ΔL = 1.9 μm in $P_{initial}$ shows that the end-effector positioning accuracy increased at 6.4 % due to the better joint error compensation.

3 Computer Simulation

The developed method of joint error maximum compensation was presented as applied to the simple 2-R robotic manipulators. The numerical solution for the optimization of end-effector pose accuracy can be found for the robotic manipulator of any complexity using manipulator Jacobian [4, 5, 7]. In order to improve end-effector pose accuracy, one may perform global or local optimization of the robotic manipulator by changing joint coordinates in the manipulator Jacobian iteratively and calculating new values of end-effector pose accuracy.The architecture of the used simulation framework is shown in Fig. 4.

In order to perform the computer simulation of 6-DOF PUMA type robotic manipulator end-effector pose accuracy improvement using joint error maximum compensation, the following software tools were used:

- "Arm Solution" (6-DOF PUMA type robotic manipulator visualization tool);
- "Accuracy Optimizer" (Excel Macros for optimizing end-effector pose accuracy);

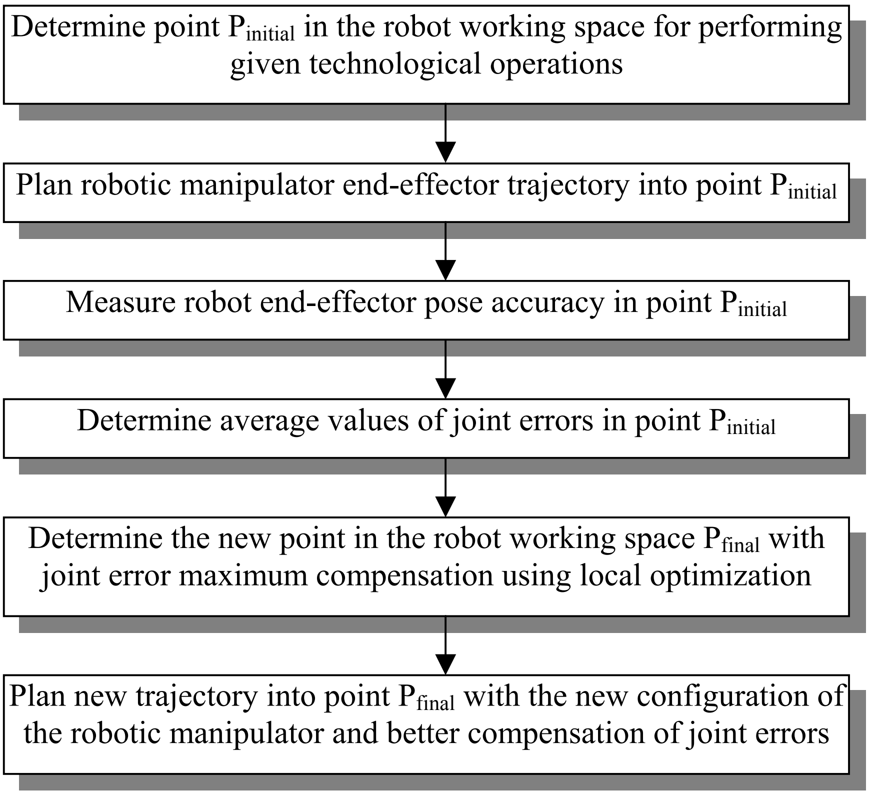

Fig. 3. Flow-diagram of method of robotic manipulator end-effector pose accuracy improvement using joint error maximum compensation

- Microsoft Excel (standard Microsoft Office tool for generating reports).

Based on the performed computer simulations, the end-effector pose accuracy of 6-DOF PUMA type robotic manipulator was improved from 10 to 15 % using the developed method in the area of the allowed 10 mm distance from the initial point.

4 Implementation

Generally, the developed method of the end-effector pose accuracy improvement using joint error maximum compenation is aimed to be used in the robotic manipulators with open-loop control systems. Currently, the number of the robotic systems with open-loop control systems with DC (direct current) and AC (alternative current) drives is relatively small. Therefore, the current research was primarily aimed to be used by the manufactures of industrial robots with stepping drives. Additionally, due to some specific stepping motor characteristics (hysteresis, stator-rotor equilibrium state, etc.), stepping drives have some positioning errors which are usually not handled at the control system level due to the complexity. This makes stepping drive based robotic manipulators the most attractive for the implementation of the developed method.

The developed method was applied at the measuring robotic system based on the stepping drives produced by at the "Planar" Co. (Belarus) for rotational joints. The industrial application allowed improving end-effector pose accuracy at the industrial site for measuring assembly parts from 5 to 15 % due to the change of the position of the end-effector in the direction of the point with maximum mutual joint error compensation.

5 Conclusion

The method of end-effector pose accuracy improvement using joint error mutual compensation for 2-R SCARA type and 6-DOF PUMA type robotic manipulators was presented. The computer simulations and industrial application confirmed the theory. The presented results provides the basis for an industrial application of joint error mutual compensation in the conventional robotic manipulators. Generally, the implementation of the developed method in the robotic systems allows improving end-effector pose accuracy from 5% to 2 times depending on the type of the robotic system and given conditions.

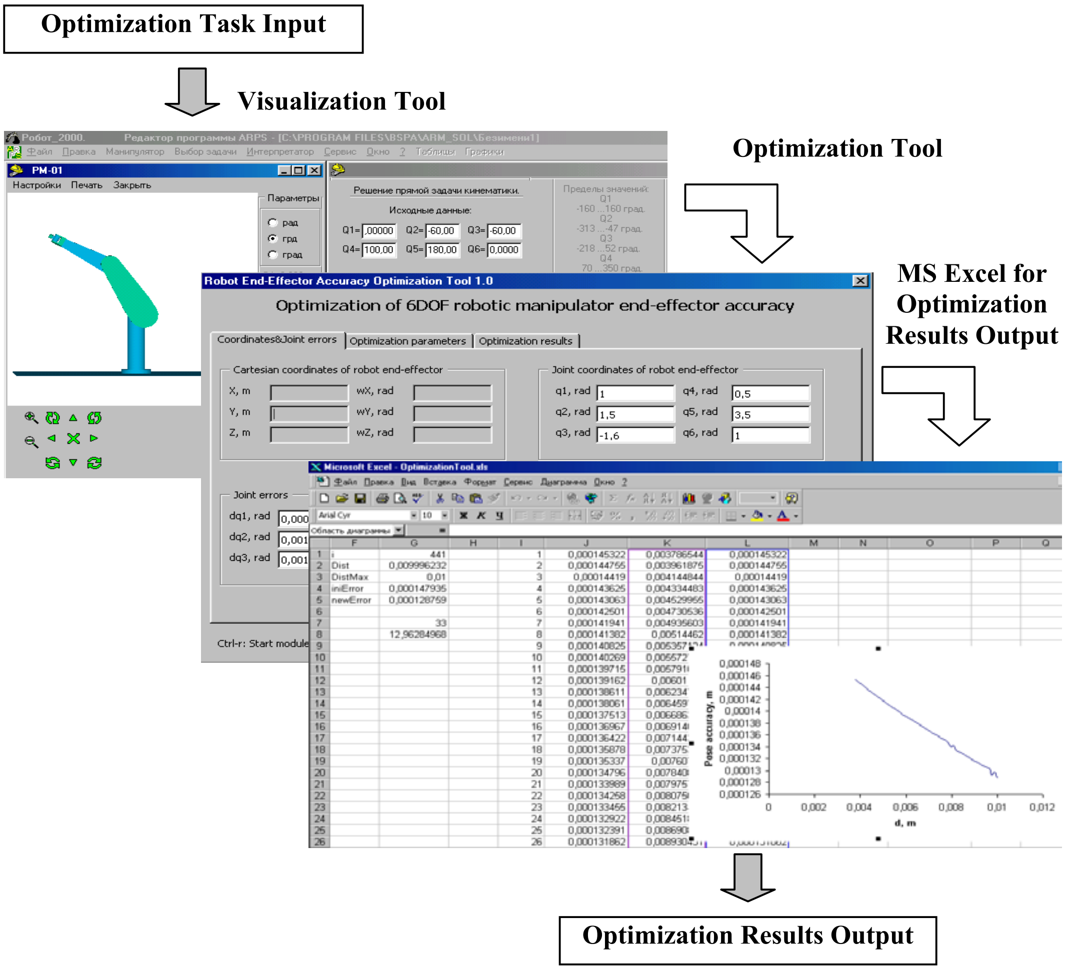

Fig. 4. Architecture of computer simulation scheme for end-effector pose accuracy optimization using joint error mutual compensation

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