# Intelligent Control for Dual-Purpose Robot-Manipulators Based on Combining Neural Network and Fuzzy Methods

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**Abstract**

The article describes an approach to intelligent control of dual-purpose and special-purpose robot manipulators based on the use of a combination of a neural network model and a fuzzy iterative algorithm. The neural network model is used to find an approximate solution to the inverse kinematics problem. The proposed fuzzy iterative method is used to refine the obtained solution and allows the robotic arm to be controlled in conditions where it is impossible to accurately identify the position of the target object of capture.

**Keywords**

Intelligent control, robot manipulator, artificial neural network, fuzzy iterative method.

## 1. Introduction

Robotization in various spheres of human activity is one of the key factors that ensure the formation and implementation of a state production, economic and defense potential. In the first case, the use of modern robotic complexes in production processes can significantly increase the productivity and efficiency for the functioning of units and assemblies being part of industrial equipment. In the second case, complex robotization of special-purpose machines is one of the priority tasks for modern domestic and foreign military doctrine, the main aim of which is to ensure the safety of personnel life and health, as they are the most important value in the implementation of special tasks, including the conduct of counterterrorism operations. Automated systems are capable of functioning in dangerous and unsuitable conditions for a human being, characterized by a high level of radiation, biological and chemical contamination, as well as reducing the physical load on personnel when performing special tasks, due to which they are increasingly used as a part of various formations.

When creating robotic systems for civil, dual and special purposes, the most widespread are sequential multi-link robot- manipulators (MRMs), which are a single kinematic chain formed by a number of series-connected links. Among the MRMs, a special place is taken by robots with an angular coordinate system. This design assumes the presence of a base link that rotates the robot in a horizontal plane relative to the vertical axis, and series-connected links with rotational joints attached to it. All other conditions being equal, manipulators with an angular coordinate system have the largest service area and, in addition, relatively small size, which ensures their versatility in solving various classes of problems.

In this regard, the development of new MRMs control algorithms, including those based on the use of intelligent information analysis technologies, can be considered a relevant scientific problem.

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## 2. Problem statement

In practice, a significant part of the problems for robotic systems control is solved taking into account the selected criteria, among which the following can be singled out:

- maximizing the movement speed of the MRM working body to a given point in space with its subsequent transfer to the final position;
- ensuring maximum accuracy for the movement of the MRM working body from one given point of the space included in its working zone to another.

The selected criteria determine the method for solving the inverse kinematics problem (IKP), consisting in determining the configuration of the MRM (the vector of generalized coordinates $q^{\rightarrow}$, which in the case of a MRM with an angular coordinate system is a vector for attached angles of links rotation) to ensure a given spatial position of the working body $k^{\rightarrow}$.

From the first criterion point of view, it is reasonable to determine the solution of the IKP as quickly as possible for moving the working body to a given point in space. The second criterion in the formalized form can be written as follows:

$$r^{*} \rightarrow \min_{r \in R} \left\{ \sum_{i=0}^{N} \Delta q_i^r \right\}$$

$$\left\| \Phi(\vec{q}_{\text{н}} + \Delta\vec{q}^{r}) - \vec{k}_{\text{к}} \right\| \leq \varepsilon \rightarrow r,$$

where $R$ – the set of vectors for generalized coordinates that are the solutions of the IKP; $r = \Delta\vec{q}^{r} = \{\Delta q_0^r, \Delta q_1^r, \ldots, \Delta q_N^r\}$ – the concrete solution of the IKP; $\Delta q_i^r$ – change in the position of the $i$-th link required to obtain the solution $r$, $\vec{q}_{\text{н}}$ – vector of angles characterizing the MRM initial position, $\vec{k}_{\text{к}}$ – vector of coordinates for the travel target point, $N$ – the number of MRM links excluding the base link; $\varepsilon$ – accuracy for finding a solution.

The criterion essence is the choice of the only vector $r*$ from the set of IKP R possible solutions, which ensures the minimum displacement of the MRM moving parts relative to the initial position.

When developing algorithms for MRM control in a real-time mode, it is advisable to implement a combination of two previously indicated criteria [1, 2]. This mode imposes special requirements on the speed index of the MRM, which in its turn depends on the information processing speed and the robot components dynamics indicators. This led to the development of the so-called combined intelligent algorithms, involving the development of solutions to place the MRM working body into the spatial region (for example, using a neural network model), as close as possible to the given coordinate, followed by a more accurate adjustment of the links angles junction vector using numerical methods [3].

Works analysis related to this approach [3, 4] shows that some aspects require additional substantiation. The noted aspects include the choice of the neural network architecture, as well as the type of numerical method in the MRM operation in real-time. This article is devoted to the solution of the stated problems.

## 3. Method proposed

In accordance with the chosen problem statement, an analysis for the neural networks structures was carried out to determine the vector of the generalized coordinates specifying the MRM configuration for its working body positioning at a given point in space $\vec{k} = (x, y, z)^T$ in the absolute coordinate system.

For special and dual-purpose robots, one of the key factors is the required memory capacity of the calculator. In this regard, a fully connected feedforward network of the multilayer perceptron type is proposed to be applied as the architecture of the neural network used at the first step of the combined method.

The main advantage of this network over the adaptive neuro-fuzzy inference system ANFIS considered in articles [3-5] is the relative simplicity of the architecture. It is also worth noting that the multilayer perceptron has a fairly high performance and does not require complex preliminary configuration.

At the second step, to refine the obtained solution, the numerical Gauss-Newton method is proposed to be used, since, in contrast to the Newton-Raphson method applied in [3], it is less resource-intensive, since it does not require the calculation of the second derivatives matrix. In this case, this method can be applied for redundant MRMs often used in practice, for which the dimension for the vector of generalized coordinates $\vec{q}$ exceeds the dimension of the vector $\vec{k}$, containing the values characterizing the gripper position.

To implement the proposed combined method, a computer program was developed, its algorithm flowchart is shown in Figure 1.

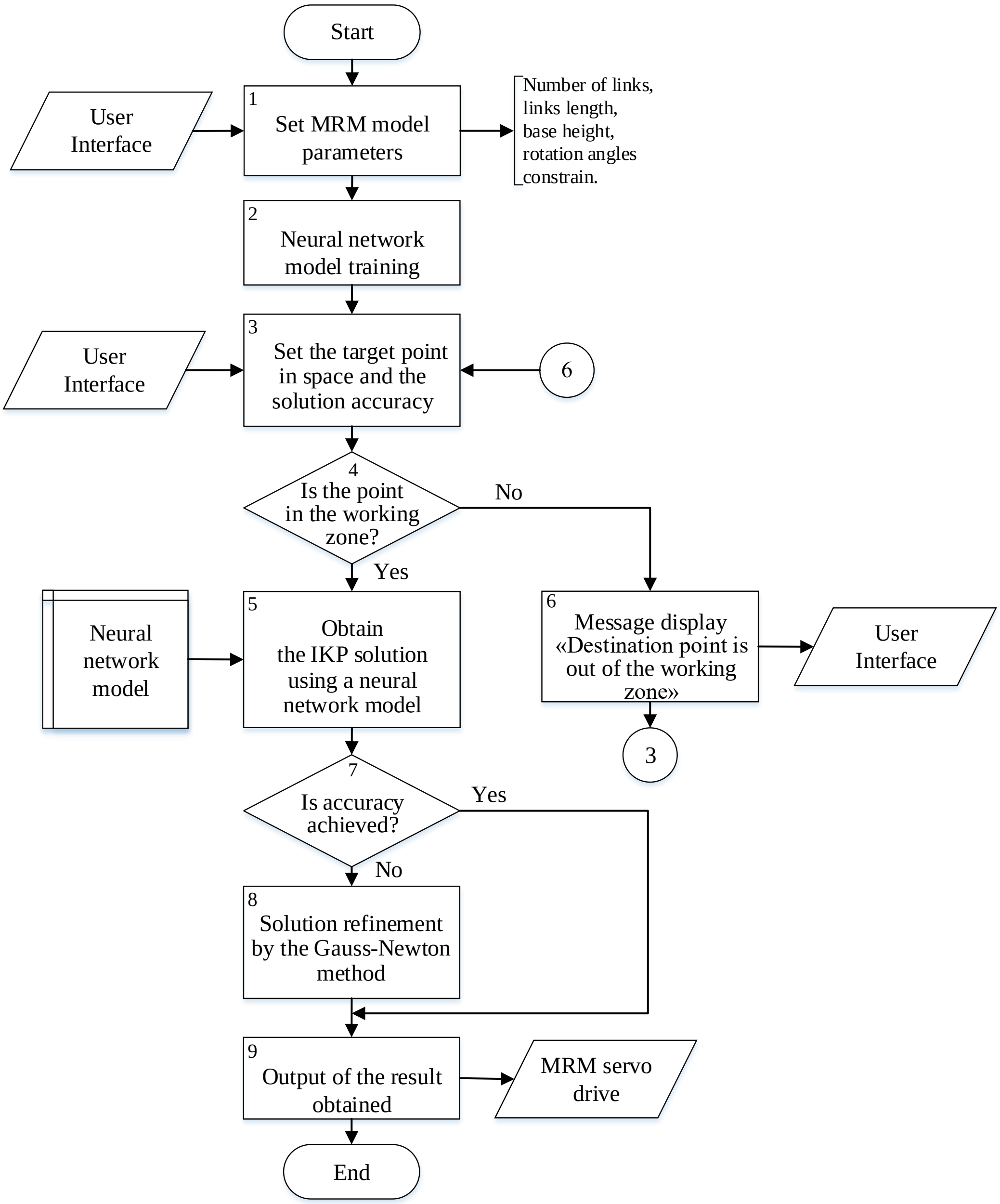


**Figure 1**: Flowchart of the combined method realization algorithm

In accordance with the flowchart, at the first step, the user sets the parameters describing the MRM physical model of the type under consideration. The step of training the neural network model is followed further, after which the program expects to receive the coordinates of the point in space to which it is necessary to move the working body of the MRM, as well as the value of the required positioning accuracy. Next, the destination point is checked for the working zone of the manipulator. If the point is out of the working zone, then an information message is displayed and the algorithm returns to the coordinate input block. Otherwise, an approximate solution is determined using a neural network model. If the user-specified accuracy has not been achieved, the resulting solution is refined using the Gauss-Newton method. At the next step, the obtained values for the elements of the generalized coordinates vector are transferred to the corresponding driving mechanisms of the MRM.

The program provides for the possibility of three-dimensional visualization of the MRM functioning process, which is shown in Figure 2.

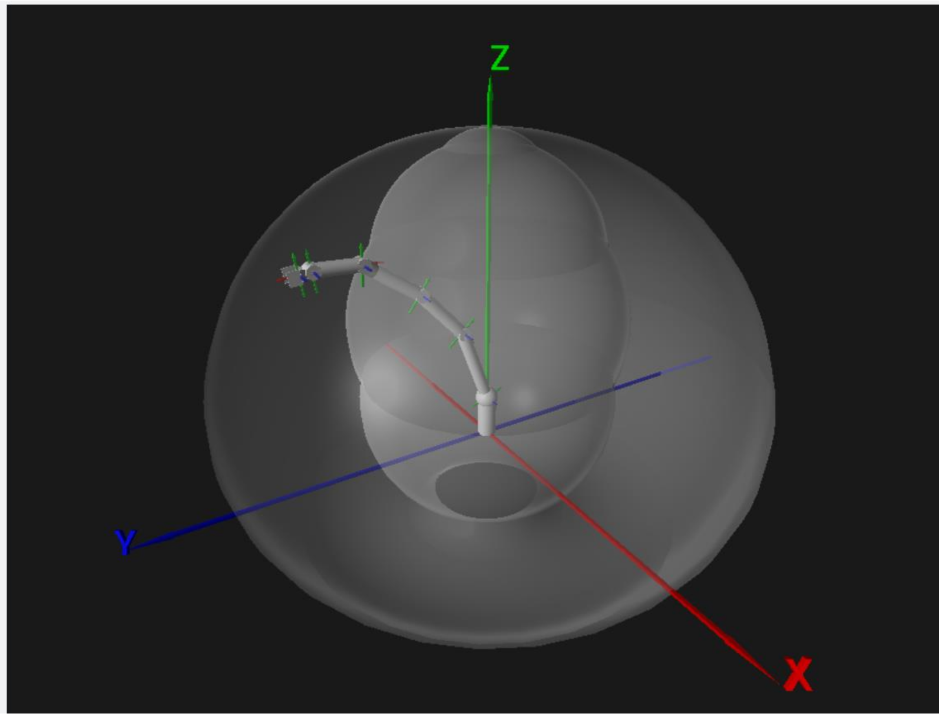


**Figure 2**: Visualization of the MRM functioning process using the proposed method

## 4. Fuzzy numerical method implementation

The situations when it is impossible to identify the position of the gripping target object due to the presence of environmental factors are possible to arise in practice. First of all, these factors can be referred to the effects that affect the systems of technical vision. This problem is especially relevant for special-purpose mobile robots operating in aggressive environmental conditions.

In case of ambiguity when identifying the exact spatial position of the target object, the area of its possible location can be described by a vector, which components are fuzzy numbers. Membership functions of fuzzy numbers are convex unimodal curves, which in general can have any shape. The specific form is determined on the basis of expert judgment by analyzing the statistical data obtained for specific uncertainty factors. As an example, the work will consider the representation of the coordinates for the target object in the form of fuzzy numbers with membership functions of a triangular shape, which form is shown in Figure 3.

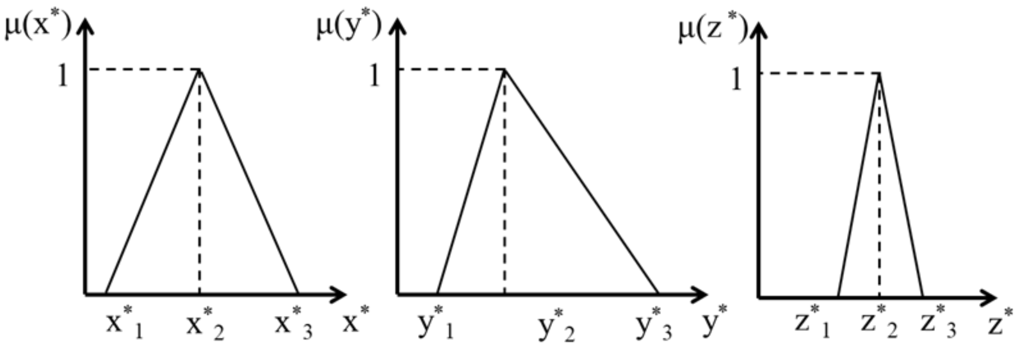


**Figure 3**: Presentation for the position coordinates of the target object in the form of fuzzy numbers with the triangular membership function

In the given setting, the direct kinematics problem (DKP) can be written in the form:

$$\widetilde{\boldsymbol{k}} = \widetilde{\Phi}(\widetilde{\boldsymbol{q}})$$

where $\widetilde{\Phi}(\widetilde{\boldsymbol{q}})$ – transformation matrix.

In general, the system describing the kinematics of the MRM with an angular coordinate system can be represented as a system of nonlinear equations:

$$\begin{cases} \tilde{x} = \left[\sum_{i=1}^{N} L_i \cdot \sin\left(\sum_{j=1}^{i} \tilde{q}_j\right)\right] \cdot \cos(\tilde{q}_0)\,; \\ \tilde{y} = \left[\sum_{i=1}^{N} L_i \cdot \sin\left(\sum_{j=1}^{i} \tilde{q}_j\right)\right] \cdot \sin(\tilde{q}_0)\,; \\ \tilde{z} = L_0 + \sum_{i=1}^{N} L_i \cdot \cos\left(\sum_{j=1}^{i} \tilde{q}_j\right). \end{cases}$$

In the specified equations system, the independent variables will also represent fuzzy numbers with a triangular membership function. In this case, the crisp coordinates values of the MRM gripper position at the initial time can be represented in the form of a degenerate triangular membership function, in which the boundary values coincide with the modal one.

To calculate the values of the cosine and sine for the angles represented by fuzzy numbers, the corresponding trigonometric functions are represented as an expansion in a Taylor series with the number of members necessary to achieve the required calculation accuracy:

$$\sin(\tilde{q}) = \sum_{n=0}^{\infty} \frac{(-1)^n \tilde{q}^{2n+1}}{(2n+1)!},$$

$$\cos(\tilde{q}) = \sum_{n=0}^{\infty} \frac{(-1)^n \tilde{q}^{2n}}{(2n)!}.$$

In general, the IKP can be formulated in the form of the following expression:

$$\tilde{\boldsymbol{q}} = \tilde{\Phi}^{-1}(\tilde{\boldsymbol{k}}),$$

where $\tilde{\Phi}^{-1}(\tilde{\boldsymbol{k}})$ – matrix inverse to the transformation matrix.

In conditions of a fuzzy set position of the target object, the fuzzy Gauss-Newton method is proposed to be used.

To find the numerical solution, the function can be defined:

$$\tilde{F}(\tilde{\boldsymbol{q}}) = \left\|\tilde{\Phi}(\tilde{\boldsymbol{q}}) - \tilde{\boldsymbol{k}}\right\|^2 \to \min|_{q \subset R^n},$$

where the square norm is the fuzzy distance between the current positioning of the MRM gripper and the set position of the target object.

Jacobian matrix:

$$\tilde{J}(\tilde{\boldsymbol{q}}) = \left\{\frac{\partial \tilde{F}_j(\tilde{\boldsymbol{q}})}{\partial q_i}, j = 0 \dots 2, i = 0 \dots N\right\}.$$

Right and left Jacobian pseudoinverse matrices:

$$\tilde{J}^{+} = (\tilde{J}^T \cdot \tilde{J})^{-1} \cdot \tilde{J}^T,$$

$$\tilde{J}^{+} = \tilde{J}^T \cdot (\tilde{J}^T \cdot \tilde{J})^{-1}.$$

The formula for calculating the next value of the algorithm is as follows:

$$\tilde{\boldsymbol{q}}^{[i+1]} = \tilde{\boldsymbol{q}}^{[i]} - \alpha_i \cdot \tilde{J}^{+}(\tilde{\boldsymbol{q}}^{[i]}) \cdot \tilde{F}(\tilde{\boldsymbol{q}}^{[i]}),$$

where $\alpha_i \leq 1$ – step size, which can have constant or variable value.

When performing iterative operations with fuzzy numbers, the effect of uncertainty "accumulation" arises, consisting of increasing the result obtained fuzziness at each successive step of the algorithm, which can negatively affect the quality of the latter. To minimize the effect of accumulation for uncertainty, the approach described in [6] is proposed to be used, consisting of using the fuzzy numbers interaction based on their modal values.

Stopping criterion can be written as follows:

$$\left|\tilde{\boldsymbol{q}}^{[i+1]} - \tilde{\boldsymbol{q}}^{[i]}\right| > \varepsilon,$$

where $\varepsilon$ – crisp value setting the calculation accuracy.

The distance between the corresponding components of the fuzzy angle vector at the last and the previous steps can be calculated as the pseudo-Euclidean metrics:

$$d_{\mathrm{E}}(A,B) = \sqrt{\sum_{i=1}^{n} (\mu_A(x_i) - \mu_B(x_i))^2}, \quad x_i \in X.$$

To carry out operations with fuzzy numbers, it is proposed to use the fuzzy interval method presented in the work [7].

## 5. Fuzzy numerical method implementation

Analysis for the MRM of dual and special-purpose use specifics showed that in order to achieve a high speed of finding an IKP solution, a two-step computational procedure is reasonable to be used. The specified two-step procedure assumes sequential application of a neural network to obtain an approximate solution and the subsequent use of a numerical method to refine it.

The choice of a structure rational variant and the neural network parameters, as well as the iterative method type, was based on the fact that the criterion for controlling the multi-link redundant MRM is to ensure high performance while observing the permissible positioning accuracy of the working body, as well as the simplicity of software implementation, which makes it possible to reduce requirements for computing devices included in the considered robotic systems. As a result, the multilayer perceptron was chosen as the architecture of the neural network, and the Gauss-Newton method was chosen as the numerical method.

A fuzzy Gauss-Newton method is proposed, allowing solving the IKP in the case when it is impossible to determine the spatial position of the gripping object accurately.

## 6. Acknowledgements

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