Structure of a Multicomponent Hybrid Model for Intelligent Control of Sequential Robot-Manipulators

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Abstract
The article deals with the building of a multicomponent system for intelligent control of a multilink robot-manipulator (MRM) on the basis of neuro-fuzzy models. This system makes it possible to take into consideration the uncertainty arising from the environmental factors influence on the MRM when controlling the MRM. The proposed control system is shown to be especially relevant for dual and special-purpose MRMs, which, due to the specifics of their solving problem, are forced to operate under conditions of dynamically changing external influences.

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

1. Introduction

Achievements in the field of robotics and automation are increasingly being applied in various areas of the military-industrial complex and the economic civilian sector. Robotic systems are used to create complex modern cyber-physical systems, complex automation for conveyor production, to work in unsafe and harmful conditions for humans, as well as to improve operation accuracy and speed.

Sequential multi-link robot-manipulators with an angular coordinate system are the most widespread among robotic systems due to their versatility in solving various classes of production and special problems. The kinematic structure for robots of this type is a system of links connected in series by means of rotational joints, a base capable of rotating about a vertical axis, and a working body, which is often represented by a gripper or a tool for performing specialized work.

During MRM operation the following groups of risk are usually distinguished:

- operational (exceeding the energy consumption specified level, equipment premature wear),
- technical (failure to achieve the specified accuracy of the gripper positioning or the specified operation speed level),
- related to occupational safety (safety for the operator and maintenance personnel in the working area during the MRM operation).

Efficiency indicators are determined taking into consideration risks, depending on the strategy and control objectives. As a rule, in practice, the main efficiency indicators for the MRMs operation are their speed, positioning accuracy and specific energy consumption.

The use for MRMs of the considered type as special modules employed as part of autonomous robotic systems, which are designed to perform research, reconnaissance, scientific and special problems are of particular interest. The main feature of such robots operation is aggressive environmental conditions that affect the efficiency indicators of their operation. On the one hand, external factors can have a physical effect on the mechanical components of the MRM structure,

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preventing the performance of the specified operations by the driving systems. On the other hand, these factors can interfere with the normal operation of the robot sensing devices, including vision systems, which in its turn leads to incorrect performance of the specified operations. As a result of these factors influence during the MRM operation, situations of complete or partial uncertainty may arise, which must be taken into consideration when organizing effective control.

In this connection, the identification of groups for uncertainty factors and the analysis of their influence on the MRM operation, as well as the creation of universal control algorithms that allow taking these factors into consideration, is an important and urgent problem. This problem solution will provide an opportunity for a wider introduction of robotic systems in various spheres of human activity, and will also increase the above mentioned indicators of the MRM operating efficiency.

2. Problem statement

In the general case, to organize the MRM control, it is necessary to solve the direct kinematics problem (DKP) and inverse kinematics problem (IKP).

DKP assumes finding, for given physical parameters of MRM coordinates, the position of its working body $\vec{k} = \{x, y, z\}^T$for a certain vector of generalized coordinates $\vec{q} = \{q_0, q_1, \dots, q_N\}^T$, which components are the rotation angles values of the corresponding links. The DKP has an unambiguous solution, which, as a rule, can be obtained analytically without any special difficulties.

IKP assumes the identification for the configuration of the MPM $\vec{q}^*$, which will allow the positioning of the working body at a given point in space $\vec{k}$. In a non-trivial case, the IKP solution is a set of vectors for the links rotation angles$\{\vec{q}_0, \dots, \vec{q}_M\}$, which values correspond to different MRM configurations, allowing the MRM working body positioning at a given point in space. In this case, obtaining a solution in analytical form is complicated by the nonlinearity of the equations obtained, therefore, finding a solution to the IKP is often possible only with the use of numerical or neural network methods [1-3].

In practice, when operating the MRM in dynamically changing environmental conditions, it is often required to provide high-speed control algorithms while maintaining the specified accuracy of operations. In this case, in order to achieve certain efficiency indicators, it is advisable to use combined methods for solving the IKP, which are based on the sequential application of a neural network model to determine an approximate solution and a numerical method to refine it.

When solving the IKP for the control of the MRM operating in real conditions, it is necessary to take into consideration various environmental factors that affect its operation.

Figure 1 shows the problem statement for the MRM control, taking into consideration environmental factors that introduce elements of uncertainty into the process of IKP solving.

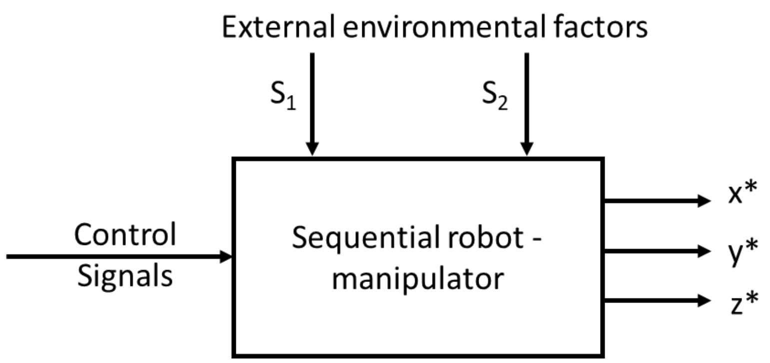

Figure 1: Problem statement for the MRM operation taking into consideration environmental factors

Uncertainty factors can be roughly divided into two groups. The first group (denoted as vector S_1 in figure 1) includes factors that affect the accuracy of determining the target object position in space. The second group of factors (denoted as vector S_2 in figure 1) includes factors that prevent the correct movements of the MRM.

The factors of the first group primarily affect the technical vision systems. For MRMs being part of autonomous robots, these factors include the presence of dust, sand, raindrops accumulating on the lenses of optical devices, as well as a limited view of the robot optical system as a whole. For industrial MRMs, these factors include variations in the shape and size of the gripped objects, etc.

The factors included in the vector S_2, primarily affect the MRM actuating mechanism. For autonomous robots, this can be a strong crosswind, air humidity. For industrial robots, corrosion and wear of moving parts, voltage change, etc. can be distinguished.

In a number of practical situations, external factors related to the selected groups significantly affect the result of MRM operation, which determines the necessity to take them into consideration when developing control actions based on the IKP solution. Figure 2 shows a diagram characterizing the possibility of taking into consideration uncertainty factors when controlling MRM using intelligent algorithms.

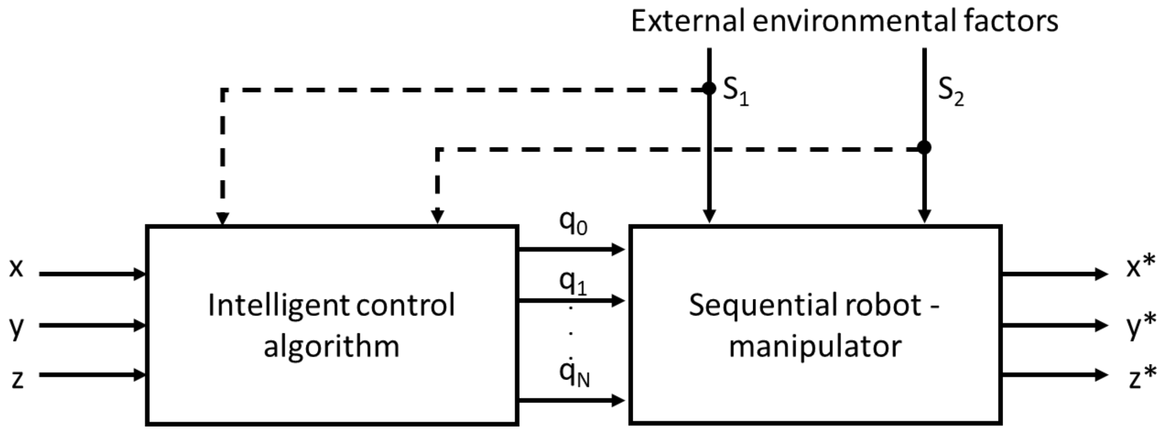

Figure 2: Uncertainty factors consideration in MRM control with the use of intelligent algorithms

Unfortunately, the classical methods for solving IKP, including those related to the group of combined ones, do not take into consideration environmental factors sufficiently.

The above stated determine the appropriateness of modifying the existing methods and algorithms that implement them for solving the IKP based on the use of fuzzy sets theory elements to reflect the influence of uncertainty factors on the result of the MRM operation, as well as building a multicomponent model that will take into consideration the uncertainty factors of the selected groups during control [4-6].

3. Structure of a multicomponent model

To consider the impact of environmental factors for the groups having been previously described, a multicomponent hybrid model of MRM control is proposed to be used, its diagram is shown in Figure 3.

The structural model includes a block to analyze the influence of external factors, three models for the direct determination of the IKP solution, a block for the formation of control actions. The block for analyzing external factors is used to identify the degree of their influence on the accuracy of determining the position of the gripped object, as well as on the dynamics of the MRM actuating mechanisms. As a result, three main groups of situations arise, each of them has its own model for solving the IKP:

- the first model is used in the absence of external factors of uncertainty or their insignificant influence on the process of MRM operation;
- the second model is used in the case of the presence of external factors affecting the ability to determine the spatial position of the target object accurately (factors included in the vector *S1*);
- the third model is used in the case of the presence of external factors that prevent the MRM from entering a given point in space by mechanical action on its actuating systems (factors included in the vector *S2*).

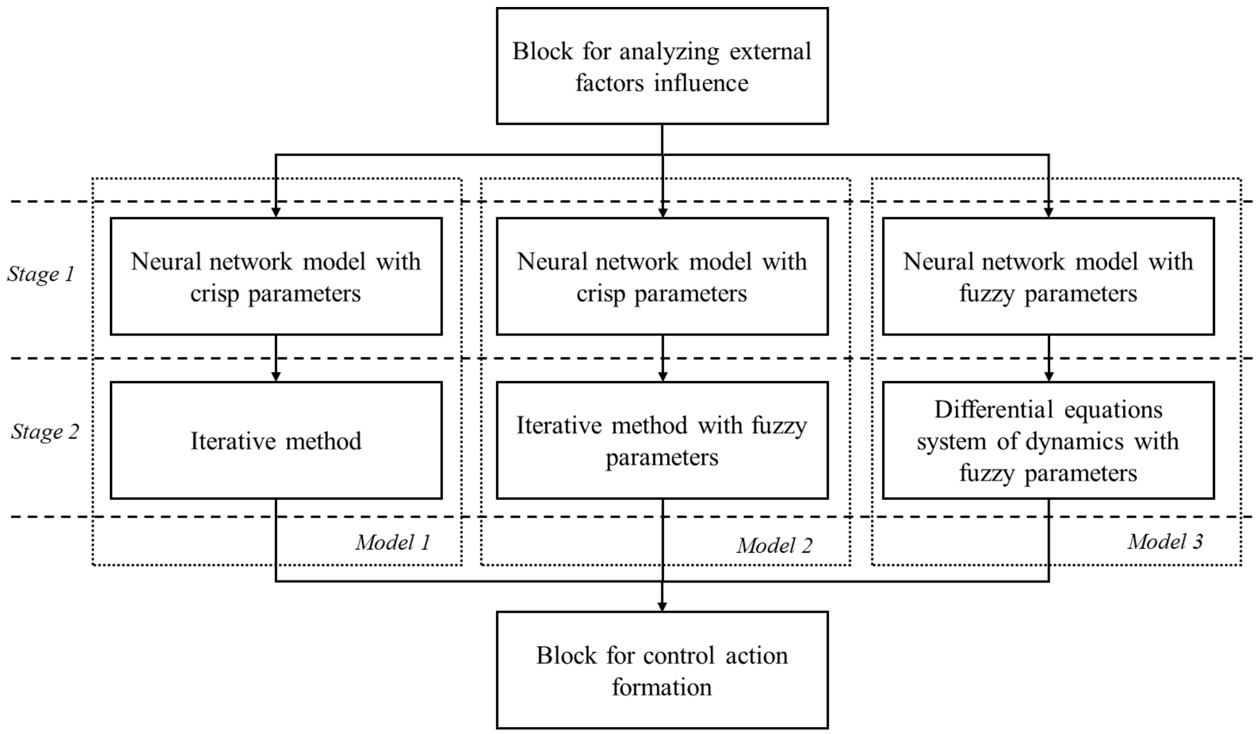

Figure 3: Block diagram for a multicomponent hybrid model of MRM control, considering the impact of environmental factors

The block to form control actions is designed to determine the output signals for transmitting them to the MRM actuating mechanisms.

The choice of a rational version for the structure of the neural network and the iterative method is based on the assumption that the criterion for controlling the multi-link redundant MRM is to ensure high operation speed while observing the permissible positioning accuracy of the working body, as well as the simplicity of software implementation, which allows the possibility of reducing the requirements for computing devices being part of the considered robotic systems. Such criteria are quite often implemented in practice when using robot-manipulators of this type in conveyor production systems, as well as autonomous robots for special and dual purposes.

In this connection, it seems rational to modify the combined method for solving the IKP on the basis of introducing fuzziness into the algorithm for implementing the iterative method, as well as substantiating the type and structure of the neural network used, considering the specifics of the environmental factors of the groups identified above.

4. Proposed method

To implement the first stage of the combined method, neural network models with various architectures can be used, the most commonly used are the following ones: multilayer perceptron, networks with radial-basis activation functions and ANFIS networks. [3,7].

As noted earlier, the choice of a specific type of neural network architecture depends on the need to take into consideration environmental factors at the first stage of the algorithms, as well as the application features of the robotic system as a whole.

When implementing control algorithms for autonomous robots, which usually have limited internal memory resources, it is preferable to use a multilayer perceptron. This type of network is easy to implement and it has sufficient performance for real-time control.

In the case of the external factors presence that prevent the correct movement of the MRM working body to a given point in space (factors included in the vector *S2*), it is advisable to use the ANFIS network, which has a more complex internal structure and considering the fuzziness due to the principles of fuzzy logic.

Various numerical algorithms can be used to implement the second stage of the combined method. The choice of a specific option depends on the requirements for the resource intensity of the computations performed, the speed of obtaining an IKP solution, as well as the algorithm convergence insurance.

When the influence of the factors included in the vector *S1* on the MRM, the position of the target object in space is impossible to be accurately identified. In this connection, the coordinates of the object can be represented as fuzzy numbers. An example of representing the components of the working body position vector in the form of fuzzy numbers with L-R type membership functions is shown in Figure 4.

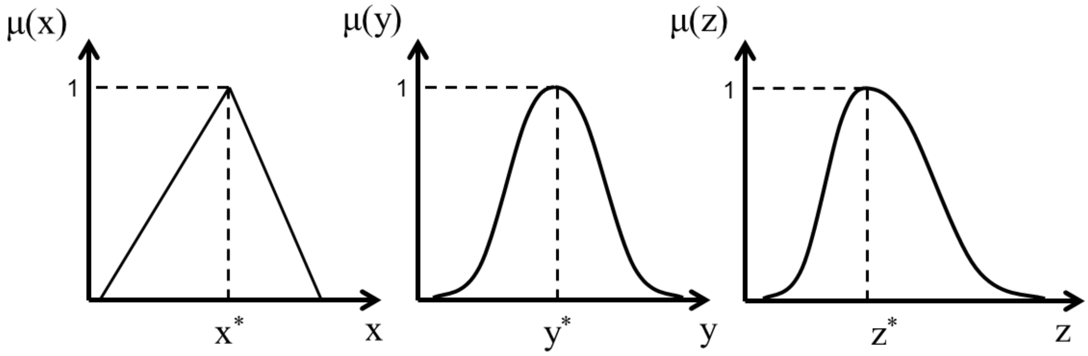

Figure 4: Presentation of coordinates for the MRM working body in the form of fuzzy numbers with membership functions of the L-R type.

In this setting the IKP can be formulated as follows:

$$\widetilde{\boldsymbol{q}} = \tilde{T}^{-1}(\widetilde{\boldsymbol{k}}), \tag{1}$$

where $\widetilde{\mathrm{T}}^{-1}(\widetilde{\boldsymbol{k}})$ – matrix inverse to the transformation matrix $\widetilde{\mathrm{T}}(\widetilde{\boldsymbol{q}})$, determined by the kinematic structure of the MRM.

The IKP solution in the form (1) can be obtained using fuzzy numerical algorithms [8], while under conditions of uncertainty, the function for finding the solution will be in the following form:

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

In formula (2), the square norm is the fuzzy distance between the given vector of the target object position in space and the vector of coordinates for the MRM working body current position. This value can be calculated, for example, as the fuzzy relative Euclidian distance:

$$d_E(A, B) = \frac{1}{\sqrt{n}} \sqrt{\sum_{i=1}^{n} (\mu_A(x_i) - \mu_B(x_i))^2}, \quad x_i \in X. \tag{3}$$

In practice, when solving the IKP, second-order numerical methods are used, as a rule. The methods of this group are based on the calculation of the Jacobi matrix, which in the considered setting will have the form:

$$\tilde{J}(\widetilde{\boldsymbol{q}}) = \left\{\frac{\partial \tilde{P}_j(\widetilde{\boldsymbol{q}})}{\partial q_i}, j = 0 \dots 2, i = 0 \dots N\right\}. \tag{4}$$

The value for the angles vector of the MRM rotation at the next algorithm iteration can be calculated by the formula:

$$\widetilde{\boldsymbol{q}}^{[i+1]} = \widetilde{\boldsymbol{q}}^{[i]} - \gamma_i \cdot \tilde{J}^{+}(\widetilde{\boldsymbol{q}}^{[i]}) \cdot \tilde{P}(\widetilde{\boldsymbol{q}}^{[i]}), \tag{5}$$

where $\gamma_i \leq 1$ – the value for the *i*-th step of the algorithm, which depending on the specific method, can be fixed or can change according to some given rule.

The algorithm stopping criterion can be written as:

$$\left|\tilde{P}(\widetilde{\boldsymbol{q}}^{[i+1]}) - \tilde{P}(\widetilde{\boldsymbol{q}}^{[i]})\right| \leq \varepsilon, \tag{6}$$

where ε – crisp value that sets the required positioning accuracy of the MPM working body.

5. Conclusion

The analysis of situations that may arise during the MRMs operation as part of autonomous robots for dual and special purposes has shown the importance of taking into consideration uncertainty factors when organizing effective control in dynamically changing environmental conditions. Two main groups of factors have been identified, that introduce uncertainty into the MRM control algorithm. The first group includes factors influencing the accuracy of determining the spatial position of the target object, the second group includes factors that have a direct impact on the MRM working body movement.

To consider the identified groups of uncertainty factors, the structure of a multicomponent hybrid model for the MRM control is proposed, which is based on the use of a two-stage procedure for solving the IKP. At the first stage, using a neural network model, an approximate solution is determined, which is then refined at the second stage using a numerical algorithm.

Various versions of the artificial neural networks architectures to implement the first stage of the multicomponent model are considered, and a general scheme for constructing a fuzzy numerical algorithm of the second order to clarify the IKP solution under uncertainty is presented.

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