

Structural-functional model of a parallel-hierarchical optical network as a systematic tool for artificial intelligence methods

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ABSTRACT

The article discusses the challenges of real-time data processing and analyzes various methods used to solve them, with a focus on image processing. It points out the limitations of existing methods and argues for the need to use more effective and modern technologies, proposing parallel-hierarchical networks as a promising solution. The article provides a detailed description of the structural-functional model of this type of network, which involves cyclically transforming the input data matrix using a "common part" criterion and an array evolution operator until a set of individual elements is formed. The proposed model is expected to improve real-time image recognition and can potentially be applied to other fields by using the "common part" criterion.

Keywords: image processing, parallel-hierarchical optical networks, parallel information encoding, criterion of common part, real-time data processing

1. INTRODUCTION

The technology of parallel data processing is becoming increasingly relevant. It is applied in various fields of public life, such as modeling physical or global processes, automation of design, conducting various complex calculations, in transport systems, and more. This technology is quite effective when building optimal transport and telecommunications networks, as well as in real-time image recognition. The use of lasers in data transmission has become relevant, requiring quick and accurate recognition of laser images^{1,2}. Accurate recognition of vehicle license plates on images from road cameras is necessary to quickly identify offenders, or, for example, to timely recognize a terrorist among passengers at airports or other transportation stations^{3,4,5}.

Parallel-hierarchical networks are a powerful tool for processing large amounts of data in real-time. Known methods of data processing, including image processing, are often insufficiently effective when the result is needed here and now. As a rule, the higher the processing speed, the lower the accuracy of the result, and to obtain greater accuracy, more time will be needed through the conduct of more complex calculations. In systems that work in real-time or process dynamic data, both speed and accuracy are important^{6,7,8}. The problem can be solved by parallel data processing. Parallel-hierarchical structures allow for fixing the components of an object and the connections between them, combining them, and thus accumulating information about the object. This significantly reduces processing time and provides accurate results.

This article presents a structural-functional model of a hierarchical network for image processing, which can be used in various fields, such as artificial intelligence systems and tools, where quick and accurate results are required.

The aim of this research is to analyze parallel-hierarchical processes of coding and information processing. The objective of the research is to develop a structural-functional model of a parallel-hierarchical network for use in artificial intelligence tools.

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2. RESEARCH MATERIALS AND METHODS

The structure of data processing is identified with a directed graph, where nodes correspond to data elements, and directed edges connecting nodes describe various dependencies between elements and are marked accordingly⁹. The concept of a parallel-hierarchical network was considered for the development of a structural-functional model. The network of PI transformations is a set of characteristics^{10,11}:

$$C \in (\Omega, A, Q^*, F^*) \in \{M_1^1(t_0); M_2^1(t_0); \dots; M_h^1(t_0); M_1^2(t_1); \dots; M_n^u(t_s)\}, \quad (1)$$

where C is the final set of sets, $h \geq 2$ – the number of output sets, $u \geq 2$ – the ordinal number of the level, $n \geq 2$ – the ordinal number of the u -th level; t_s is the step at which the corresponding set was formed, $S \geq 1$, t_0 the first or initial step where the output sets of the first level are formed. The final set A consists of:

$$A = \{a_1^1(t_1); a_2^1(t_1); \dots; a_h^1(t_1); a_1^2(t_2); \dots; a_n^{u'}(t_s)\}, \quad (2)$$

where $u' \geq 2$ – the level number; $n' \geq 1$ – the number of the set to which the element belongs; t_s – the time at which the corresponding element is formed.

$M_i^j(t_s)$ – the output set for the j -th level, F^* – the criterion by which an element is selected from the set, $a_i = F^*(M)$, $a_i \in M$, Q^* – the function of transforming set $Q_{a_i}^*(M) = M'$, and Ω – the set of sets.

Each of the sets M is transformed by a single network algorithm, and all sets are processed in parallel. From the set M_i , one element a_{ij} is selected and the element $a_i^1(t_1) = a_{ij}$ is an element of the network C .

The process of transforming an array of information is represented by a matrix of size $n \times I$, that is, a matrix:

$$A = \begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{pmatrix}, \quad (3)$$

where the elements of the output matrix Y are random variables with values of functions with any distribution law:

$$a_j \in N \cup \{0\}, 1 \leq j \leq n, n \geq 1.$$

The matrix was then transformed based on the proposed "general part" criterion F^* ^{9, 10}. An example of such a criterion could be the selection of the smallest (largest) element of the matrix A , selection based on a functional law, associative selection, and so on.

Let $a_i, 1 \leq i \leq n$ be the chosen element. Using the F^* criterion, a new matrix A_i was constructed, denoted by the index of the chosen element of matrix A , where $F^* a_n = a_n^i$:

$$A_i = \begin{pmatrix} a_1^i \\ a_2^i \\ \vdots \\ a_n^i \end{pmatrix}. \quad (4)$$

The matrix A_i corresponds to the selected element a_i , and a similar procedure was applied to it. Using the general part criterion F^* , an element was chosen from it, for example, $a_j^i, 1 \leq j \leq n$, and a matrix A_j was constructed by transforming the A_i matrix.

$$A_j = \begin{pmatrix} a_1^j \\ a_2^j \\ \vdots \\ a_n^j \end{pmatrix}, \quad (5)$$

where $a_k^j = F^* a_k^i, 1 \leq k \leq n$.

The process of transforming these matrices continued until a matrix consisting of zeros was obtained. Let this be the matrix:

$$A_\tau = \begin{pmatrix} a_1^\tau \\ a_2^\tau \\ \vdots \\ a_n^\tau \end{pmatrix}. \quad (6)$$

thus: $F^* A = A_b$, $F^* A_i = A_j$, ..., $F^* A_s = A_\tau$.

From the selected elements $a_i, a_j^i, \dots, a_\tau^s$, a new matrix can be formed as follows¹¹:

1) In the first column, all selected elements that are in the process of transforming the matrices are written, i.e., the first elements of each row.

2) In the row corresponding to an element found in the initial matrix, a matrix with all its zeros replaced by ones and all other elements set to zero is written. Similar operations are performed for all other matrices of size $n \times 1$, which are written as matrices of size $1 \times n$.

Then the matrix has the following form:

$$B = \begin{pmatrix} a_i & a_{11}^i & a_{12}^i & a_{13}^i & \dots & a_{1n}^i \\ a_j^i & a_{21}^j & a_{22}^j & a_{23}^j & \dots & a_{2n}^j \\ a_k^j & a_{31}^k & a_{32}^k & a_{33}^k & \dots & a_{3n}^k \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots \\ a_\tau^s & a_{s1}^\tau & a_{s2}^\tau & a_{s3}^\tau & \dots & a_{sn}^\tau \end{pmatrix}, \quad (7)$$

in this case, $a_{\alpha\beta}^j = 0 \vee a_{\alpha\beta}^j = 1, 1 \leq \beta \leq n, 1 \leq \alpha \leq S, 1 \leq j \leq S$.

The size of the resulting matrix is $S \times (n + 1)$.

In this matrix, there are $n + 1$ columns resulting from the construction of matrix B, and the number of rows is $1 \leq S \leq n$. Moreover, $S = 1$ if matrix A is zero, and if matrix A has no identical elements and contains no zeros, then it is obvious that $S = n$. $F^{(*)'}$ denotes the transformation inverse to transformation F^* .

The process of encoding and decoding the array of information is unambiguous, i.e., $A \leftrightarrow B$ ^{10,12}. Then, it follows that the decoding process has the same number of cycles as the encoding process. The sequence of decoding cycles is strictly the reverse of the sequence of encoding cycles, and $F^{(*)'} = F^*$.

Next, a modified principle of encoding an array of information was considered, given by matrix A. In general, the information is piecewise continuous, so there are positions in this matrix where the information in the rows is missing. Thus, matrix A has the following form:

$$A = \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ \vdots \\ a_n \end{pmatrix}, n \geq 1, \text{де } a_i \in N \vee \{0\}, 1 \leq i \leq n. \quad (8)$$

The accuracy index was denoted by δ , and elements $|\delta| \leq k, k = 0, 1, 2, \dots$ are zeroed out with this index. Matrix A is transformed according to the same criterion F^* . Let a_i be the element selected from matrix A by criterion F^* , where $a_i, 1 \leq i \leq n$. Matrix A is transformed into matrix A_i and is denoted according to the number of the selected element from matrix A. If zero elements are formed in matrix A, they are denoted by 0^0 . The maximum deviation of the element value from zero, at which the value of the transformed element is still zeroed out, was taken as K. Then, in addition to the 0^0 elements, the matrix A_i contains elements of the following type: $0^{-k}, 0^{-k+1}, \dots, 0^{k-1}, 0^k$. The same procedure was performed on matrix A_τ . The process continued until a matrix was obtained in which elements from set N are absent. In general, this process can be represented schematically as follows:

$$\begin{array}{ccccccc}
A & \rightarrow & A_i & \rightarrow & A_j & \rightarrow & A_s \\
\begin{pmatrix} a_1 \\ a_2 \\ \dots \\ a_4 \\ a_5 \\ \vdots \\ a_n \end{pmatrix} & & \begin{pmatrix} \theta^*(a_1) \\ \theta^*(a_2) \\ \dots \\ \theta^*(a_4) \\ \theta^*(a_5) \\ \vdots \\ \theta^*(a_n) \end{pmatrix} & & \begin{pmatrix} \theta^2(a_1) \\ \dots \\ \theta^2(a_4) \\ \theta^2(a_5) \\ \vdots \\ \theta^2(a_n) \end{pmatrix} & & \begin{pmatrix} \theta^s(a_1) \\ \dots \\ \theta^s(a_5) \\ \vdots \\ \theta^s(a_n) \end{pmatrix} \\
F^* a_i & & F^* \theta^*(a_j) & & \dots F^* \theta^{S-1}(a_s) & &
\end{array} \quad (9)$$

where θ^* – transformation according to the general part criterion, $\theta(\theta(a_i))$ – denoted by $\theta^2(a_i)$, and so on. Then, $\theta^s(a_1^2), \dots, \theta^s(a_s), \dots, \theta^s(a_n) \in 0^{-k}, 0^{-k+1}, \dots, 0^{k-1}, 0^k$, and there are no other elements in the matrix A_s .

If no elements from the set $0^{-k}, 0^{-k+1}, \dots, 0^{k-1}, 0^k$ are formed during the transformation process in the last cycle, then these elements are not present in the next cycle. For example, if the element $\theta^*(a_2) \in 0^{-k}, 0^{-k+1}, \dots, 0^{k-1}, 0^k$ in matrix A_i , then the transformation process on it stops and this element is not present in matrix A_j . It is important to know in which cycle the array transformation becomes zero and whether there are elements adjacent to it that have become zero in the same cycle with the same approximation.

If at this stage, two or more elements become zero with the same approximation, and all of them are in a row without any missing rows between them, useful information may be lost. To prevent this, it is sufficient to record the coordinates of the first and last elements in the formed mini-array, whose elements are the same element from the set $0^{-k}, 0^{-k+1}, \dots, 0^{k-1}, 0^k$.

3. MODELLING

In this case, there is no need to preserve information about the elements between them. Then the proposed encoding method is similar to the method of series encoding⁶.

If there is no exactly the same element adjacent to an element (for example, as in $\theta^*(a_2)$ in matrix A_i), then all information about this element is valuable. As a result of encoding, an ordered array of elements $F^* a_i, F^* \theta^*(a_j), \dots, F^* \theta^{S-1}(a_s)$ and $2k + 1$ arrays of elements $0^{-k}, 0^{-k+1}, \dots, 0^{k-1}, 0^k$ will be formed. Each of the arrays consists of the same element. That is, as a result, a matrix Y is formed, similar to matrix B , and each found element corresponds to a matrix with the same index (10).

$$Y = \left(\begin{array}{c|ccc} F^* a_i & \cdot & \theta^*(a_2) & \dots & \theta^*(a_p) \\ F^* \theta^*(a_j) & \theta^2(a_1) & \dots & \theta^2(a_m) & \\ \vdots & & & & \\ F^* \theta^{S-1}(a_s) & \dots & \theta^s(a_s) & \dots & \theta^s(a_n) \end{array} \right), \quad (10)$$

where $1 \leq p, m, S \leq n$; $\theta^R(a_i) \in \{0^{-k}, 0^{-k+1}, \dots, 0^0, \dots, 0^{k-1}, 0^k\}$, $1 \leq l \leq S, 1 \leq i \leq n$

In the first column of the matrix, all selected elements are formed in the order of their selection in the process of matrix transformations. The elements corresponding to the selected element (contained in the first column) of the matrix are written in rows. Only elements from the set $0^{-k}, 0^{-k+1}, \dots, 0^{k-1}, 0^k$ are formed in the matrix (in their positions). Moreover, only the coordinates of the elements that limit the same elements of the array are remembered.

Similar to the first discussed encoding principle, the process of encoding and decoding the information array is unambiguous, that is, $A \leftrightarrow Y$. For the general case, not a set of numbers, but a series of functions whose arguments are time values were considered.

A series of functions were considered¹²:

$$f_1(t_i), f_2(t_i), \dots, f_n(t_i), \quad (11)$$

where $i = 1, 2, 3, \dots$.

Then the essence of the transformation was to represent the array of functions by a single generalized function, the arguments of which are also time values.

Let there be several rows of functions:

$$f_1, f_2, \dots, f_n; \varphi_1, \varphi_2, \dots, \varphi_m; \psi_1, \psi_2, \dots, \psi_k; n, m, k = 1, 2, 3, \dots \quad (12)$$

The series of these functions will define the corresponding arrays of numbers, which represent arrays of function values from the same time argument $t_i, I = 1, 2, 3, \dots$. At time t_i , these series of functions have the following form:

$$f_1(t_1), f_2(t_1), \dots, f_n(t_1); \varphi_1(t_1), \varphi_2(t_1), \dots, \varphi_m(t_1); \psi_1(t_1), \psi_2(t_1), \dots, \psi_k(t_1) \quad (13)$$

This system of function series is denoted by $S(f_1, \dots, f_n, \varphi_1, \dots, \varphi_m, \psi_1, \dots, \psi_k)$. In this array, function values are chosen from the argument t_j , and the selection is based on the criterion of the general part. In general, the criterion for selecting the general part can have a discriminant (numerical) and structural, physical, and intellectual sense.

The specific use of the parallel-hierarchical transformation for different tasks depends on the type of criterion, the choice of the general part F^* , and the corresponding Q^* -transformation type. From the obtained arrays (13) based on the F^* criterion and Q^* -transformation, a new array is formed. The resulting array is a second-order array and is transformed using the same algorithm. This transformation process is defined as a "vertical" transformation. The same algorithm was applied to arrays of the form (13). This process of array transformation was defined as a "horizontal" transformation, and thus all arrays obtained in this way are first-order arrays.

First-order arrays were transformed until they became zero, creating second-order arrays in the process.

Second-order arrays were also transformed using the F^* general part criterion. As a result of processing second-order arrays, a third-order array was formed, which was transformed using the algorithm described above for a first-order array. Thus, arrays of each order were also transformed horizontally until a zero array was obtained. This process continued until zero arrays were formed horizontally, and initial information was formed to construct new arrays vertically. Arrays located at different levels change horizontally over time. This process is the evolution of the array⁹, and the Q^* transformation in this case is defined as the operator of array evolution.

Let F^* be the criterion for selecting. Here, the transformation is denoted by θ , and by $\theta(f_i(t))$ – the transformed element $f_i(t)$. If the element is transformed twice, its notation is $\theta^2(f_i(t))$, etc. When transforming arrays horizontally, each of the arrays becomes zero at its step. Without violating continuity, F^* was selected for the second-order array for which the corresponding transformation has the form of an integral operator with a kernel.

$$\theta^3(\psi_{p_{S+1}}(t), \varphi_{j_1}(t), \theta(f_{i_1}(t))) \quad (14)$$

This array of elements is an array of values of some function $W(t_i)$, where $i = 1, 2, 3, \dots$. For each system of function series, its corresponding function $W(t)$ can be constructed in this way. Since only unambiguous criteria should be used in the process of transforming systems of function series, each subsequent state of the system (after this transformation is performed) is in equilibrium with the previous one. This shows that there is a one-to-one correspondence between each system of series and its corresponding function $W(t)$, i.e.:

$$\theta(S(f_1, \dots, f_n, \varphi_1, \dots, \varphi_m, \psi_1, \dots, \psi_k)) \rightarrow W(t) \quad (15)$$

Based on this, a generalized structural-functional model of parallel-hierarchical transformation for an array of functions was constructed.

$$F^*[\theta^i(f_1(t), f_2(t), \dots, f_n(t))] = \cup_{\theta_{\lambda}^{k-1} F_{i-1}^*} F^* \left[\theta_{\vee} \left(F_{i+2}^* \left(f_{\theta^i}(t) \right) \right) \right] \quad (16)$$

where $i = 0 \div S$, and i takes values sequentially from 0 to $i \leq S$, the index $i + 2$ in F_{i+2}^* indicates the application of the operator F_{i+2}^* $i + 2$ times. It was assumed that:

$$\theta^0(f_1, f_2, \dots, f_n) = (f_1, f_2, \dots, f_n), k = 1, 2, 3, \dots, l = 1, 2, 3, \dots \quad (17)$$

In the model given by equation (16), elements obtained at each level with the same "degree" θ are grouped into arrays, on which the next transformation θ and the action of the operator F^* are performed. The right to such grouping is possessed by elements that satisfy the grouping criterion, that is, those with a degree of θ and an index of F^* that is one less. The subscript \vee for θ indicates that for an element that satisfies the grouping conditions, it is necessary to perform the θ transformation and the F^* operator once.

The developed structural-functional model can be applied to any number of functions in the processed array of information. It retains its form regardless of the number of functions.

4. CONCLUSIONS

The article discusses the main problems of real-time information processing, especially in conditions of constantly increasing volumes of such information. An analysis of recent research on this issue was conducted. It was found that most of the methods used for data processing process them sequentially, which requires more time to obtain a result. The use of parallel-hierarchical optical networks made it possible to process data in parallel, which greatly reduces time costs.

The main characteristics that a parallel-hierarchical network should contain were considered. Based on them and on the basis of parallel-pyramidal coding, a structural-functional model was developed. According to the model, the input data matrix is cyclically transformed based on the proposed criterion "general part" F^* and the Q^* array evolution operator. The process continues until a set of individual elements is formed, which will be the result of the transformation.

The structural-functional model works according to the same algorithm regardless of the number of input functions. At the same time, input data is processed in parallel, which means that the speedup will depend not only on the encoding-decoding algorithm but also on the number of threads in which information is processed. The limitation on the number of threads, and therefore the speed of network operation, is imposed by the amount of memory and the computing power of the device on which the network is running.

The developed model can be used for various tasks since the "general part" F^* criterion can be any: numerical, structural, physical, or intellectual. Each type covers a wide range of tasks, and therefore expands the practical value of the developed model.

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