Automatic Synthesis of Multilevel Automata Models of Biological Objects

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Abstract. In the paper the problem of high computational complexity of synthesis is discussed. Existing models and methods of synthesis don't allow build models of biological objects and systems. The complexity can be significantly reduced due to considering multilevel objects models instead of single level models. The new problem statement for multilevel synthesis is given. To build the models a new method based on inductive and deductive approaches is proposed. To describe the new multilevel models of the objects the theory of automata models is extended to the case of multilevel relatively finite operational automata models. Results of modeling of dynamics of the acid-base state in cavernous sinus of patients with cardiac surgical pathology during the postoperative period in the operating room and in the cardio-resuscitation unit are given.

Keywords: Biological objects · Multilevel automata · Automatic synthesis

1 Introduction

One of the current scientific tasks in the field of biology and medicine is to synthesize models of observed objects [1, 2]. The presence of such models allows predict possible events that refer to past experience, justify and implement targeted actions. The diversity of the observed objects is great. At the physical level they are characterized by the results of their parameters measurements. The time series of measured parameters have temporal, amplitude, frequency, and phase characteristics. At logical levels objects are described by sets of structural properties. There are multiple relations between the elements of the objects that reflect in their descriptions at both levels. From this point of view, the synthesis of observed objects models can be considered as the binding of elements of data about these objects. Known methods of inductive and deductive

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synthesis are applicable for such binding [3–16]. Inductive methods of synthesis include methods of agreement, difference, concomitant variations, residues, and others. Using the methods of inductive synthesis, it is possible to move from the time series of the results of parameters measurements to small models of the objects. Deductive synthesis is based on the results of inductive output. It allows synthesize more complex models. For deductive synthesis various implementations of resolution methods, inverse and combined conclusion methods are used.

Despite of the achieved results in the field of automatic synthesis of observed objects models, the following problems remain unsolved. They include reducing the complexity of the synthesis and increasing the efficiency of solving applied problems using the obtained models. Traditional methods of automatic synthesis of such models in many respects do not meet the needs of practice in the field of biology. They require considerable spent of time on obtaining desired solutions. In addition, due to the imperfection of the obtained models, it is impossible to ensure the high efficiency of solving applied problems such as estimating objects state, forecasting events and managing the process of achieving required objects state.

One of the promising approaches to the improvement of such synthesis is an automatic construction of multilevel automata as observed objects models. In the interests of this it is necessary to have appropriate models, methods and algorithms.

2 Problem Description

Let us consider the problem of automatic synthesis of multilevel automata as models of observed objects. As automata structures for formal description of the objects models relatively finite operational automata [17] are used. The generalized structure of the process of models formation (obtaining, pre-processing of information and direct synthesis) is represented in Fig. 1, where RFA 1, …, N are relatively finite operational automata.

According to the process of models formation, information about observed objects can be obtained by passive or active means of observation. Due to the fact that the data received from objects is generally heterogeneous, it is transformed to a homogeneous form. For this data is represented as a finite set of time series. For each of them time,

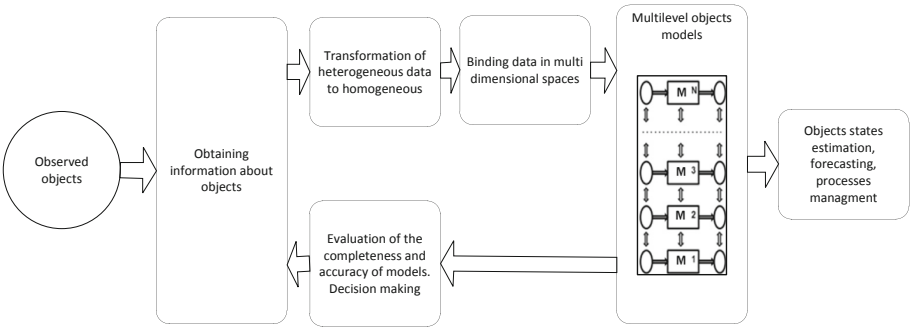

Fig. 1. The structure of the process of obtaining, preprocessing and synthesis of multilevel automata as models of observed objects

frequency or time – frequency representations are formed. The amplitude and phase characteristics of time series are frequency and phase functions. With such a representation, it is possible to talk about spatial and temporal binding, and operate on the lower level with single pulses. Linking can be carried out both within segments of single time series and between different time series or sets of time series.

It is required that, as a result of such linking, multilevel models of the observed objects can be synthesized as multilevel relatively finite operational automata (MRFA). In this regard, it is necessary to develop an appropriate method and algorithms for the synthesis of such models.

3 Features of MRFA and Synthesis Efficiency Criteria

In the interest of developing a method of synthesis of multilevel relatively finite automata as models of observed objects, let's define their features.

Every one-level RFA_r at the r-th moment of time is defined by a set of ten parameters:

$$RFA_r = \{\bar{d}_{a_r}, \bar{d}_{b_r}, \bar{d}_{c_r}, F_r^b, F_r^c, DA(\bar{d}_{b_{r-1}}), DB(\bar{d}_{b_{r-1}}), DC(\bar{d}_{b_{r-1}}), FB(\bar{d}_{b_{r-1}}), FC(\bar{d}_{b_{r-1}})\},$$

where $\bar{d}_{a_r}$ - input vector; $\bar{d}_{b_r}$ - internal state parameter vector; $\bar{d}_{c_r}$ - output state parameter vector. Transition functions F_r^b of the automata from one internal state to another and functions of the outputs F_r^c are defined as:

$$\bar{d}_{b_{r+1}} = F_r^b(\bar{d}_{a_r}, \bar{d}_{b_r}), \quad , \bar{d}_{c_r} = F_r^c(\bar{d}_{a_r}, \bar{d}_{b_r})$$

States $\bar{d}_{b_r}$, $\bar{d}_{c_r}$, $\bar{d}_{a_r}$ and functions F_r^b, F_r^c, must satisfy the conditions at the r-th moment of time:

$$\bar{d}_{a_r} \in DA(\bar{d}_{b_{r-1}}),\ \bar{d}_{b_r} \in DB(\bar{d}_{b_{r-1}}),\ \bar{d}_{c_r} \in DC(\bar{d}_{b_{r-1}}),$$
$$F_r^b \in FB(\bar{d}_{b_{r-1}}),\ F_r^c \in FC(\bar{d}_{b_{r-1}}).$$

According to these conditions, the state of the input of the automata at the r-th instant of time is limited to the set $DA(\bar{d}_{b_{r-1}})$ of admissible states defined relatively to the r-1 instant of time. The internal state of the automata at the r-th moment must relate to the set $DB(\bar{d}_{b_{r-1}})$ of its admissible internal states. There are also restrictions on the possible states of the output of the automata. These states should relate to the set $DC(\bar{d}_{b_{r-1}})$. In addition, the transition function F_r^b implemented by the automata at the r-th moment must be included in the set $FB(\bar{d}_{b_{r-1}})$ of admissible functions. The set $FB(\bar{d}_{b_{r-1}})$ of transition functions reflects the system of commands specific of the automata at the r-th moment. Outputs functions F_r^c must belong to the set $FC(\bar{d}_{b_{r-1}})$ of admissible functions.

The transition from automata RFA_r to automata RFA_{r+1} is defined as:

$$F_r^b : RFA_r, \bar{d}_{a_r} \rightarrow RFA_{r+1}.$$

Taking this into account, to construct multilevel (hierarchical) relatively finite operational automata as models of observed objects, basic sets of admissible parameters of RFA are selected:

$$HRFA^0 = \left\{DA^0, DB^0, DC^0, FB^0, FC^0\right\}.$$

From the elements of these basic sets it is possible to form admissible sets of parameters of higher i-th levels,

$$HRFA^i = \left\{DA^i, DB^i, DC^i, FB^i, FC^i\right\}.$$

As a result, multilevel relatively finite automata can be characterized by admissible sets of parameters at different levels of the hierarchy:

$$HRFA^0 \Leftrightarrow HRFA^1 \Leftrightarrow \ldots.. \Leftrightarrow HRFA^i \Leftrightarrow \ldots.. \Leftrightarrow HRFA^K.$$

Considering that in each $HRFA^i = \{DA^i, DB^i, DC^i, FB^i, FC^i\}$ admissible sets change over time, they can be represented as dependent on internal states: $HRFA^i = HRFA^i(\bar{d}_{b_{r-1}^i})$.

In some cases, by expanding the set of internal states of automata to the states of its output, it is possible to obtain automata with a truncated set of the parameters, but with the preservation of properties of the parameters restructuring:

$$HRFA_r = \{\bar{d}_{a_r}, \bar{d}_{b_r}, F_r^b, DA(\bar{d}_{b_{r-1}}), DB(\bar{d}_{b_{r-1}}), FB(\bar{d}_{b_{r-1}})\}.$$

In the logical form the transition functions of automata from one state to another can be represented as $F_r^b(\bar{d}_{a_r}, \bar{d}_{b_r}) \rightarrow \bar{d}_{b_{r+1}}$.

The considered automata is a completely reconstructable model. Elements of the upper levels of such model are represented as a set of other interrelated elements of lower levels. From a formal point of view, the transition from one level to another can be reduced to the restructuring of the admissible sets of parameters.

In conditions when the available data are insufficient for the synthesis of automata models, incomplete structures can be constructed. In such models there are parameters of the automata, which are partially defined. The completeness of the description of automata depends on the ratio of the number of its parameters and the number of parameters of the complete automata. It is proposed to determine such completeness Q_r at the r–th instant of time as

$$Q_r = 1 - \frac{1}{c}\sum_{j=1}^{c} q_{jr},$$

$$q_{1r} = \frac{|M_1(DA(d_{b_{r-1}})) - Z_1|}{Z_1},\ q_{2r} = \frac{|M_2(DB(d_{b_{r-1}})) - Z_2|}{Z_2}, q_{3r} = \frac{|M_3(DC(d_{b_{r-1}})) - Z_3|}{Z_3}$$

$$q_{4r} = \frac{|M_4(FB(d_{b_{r-1}})) - Z_4|}{Z_4},\ q_{5r} = \frac{|M_5(FC(d_{b_{r-1}})) - Z_5|}{Z_5}$$

where $M_1, M_2, \ldots, M_5$ - the capacities of the formed sets of states values and functions of transitions and outputs characterizing automata at the r–th moment; $Z_1, Z_2, \ldots, Z_5$ - admissible values of these capacities; c - a coefficient assigned according to the number of types of automata parameters, c = 5. For complete automata $Q_r = 1$. For automata whose parameters are not defined, the indicator value is zero.

Taking this into account, the models of the observed objects in the form of multilevel relatively finite operational automata with a level of the completeness not lower than the specified are synthesized based on minimizing the time for building models. In some cases when the time for synthesis is limited the construction of an efficient model is possible in trying to achieve the maximum of Q_r.

4 Synthesis Method

To solve the problem of automatic synthesis of MRFA of observed objects considering the results [18, 19] a method based on the combined use of inductive and deductive approaches is proposed. At the first stage, an inductive synthesis of a set of local multilevel automata is carried out, and at the second stage, large structures through deductive synthesis are constructed. Below the new algorithms that form the basis of this method are proposed.

4.1 Algorithm of Inductive Multilevel Synthesis

Recall that according to the above statement of the problem, the initial data for observed objects models synthesis can be sequences of sets of parameters measured values. For the automatic inductive synthesis of MRFA based on the analysis of such sequences, the following steps are proposed:

1. Analysis of sequential sets of parameters values at a given time interval $T = \sum_{j=0}^{N-1} T_j$, where T - a temporary pause between adjacent sets of single measurement on this interval.
2. Definition of admissible sets $\{DA^0, DB^0, DC^0, FB^0, FC^0\}$ characterizing the synthesized multilevel relatively finite automata at the zero level. Given that for a zero level $DA^0 = DB^0 = DC^0$, for determining DA^0, DB^0, DC^0 it is enough to find the set of all possible variants of the analyzed sets of single values.

3. Formation of the sets FB^0, FC^0 of admissible functions of transitions and outputs is made in the following way. For example, using the method of least squares, let us carry out the synthesis of private functions connecting adjacent sets of values taking into account previous events. Based on the analysis of these particular functions, it is possible to form sets FB^0, FC^0.
4. Definition of DA^i, DB^i, DC^i for the i-th levels of the hierarchy of synthesized relatively finite automata. To do this, when analyzing sequential sets of values, it is proposed to additionally identify the relative frequencies of the appearance of stable local structures of given scales. Having identified such structures, each of them can be encoded at higher levels of the hierarchy of the automata in its own way, but in other spaces DA^i, DB^i, DC^i defined for the i-th levels of the hierarchy.
5. Formation of FB^i, FC^i. For this purpose, it is proposed to analyze stable combinations of particular transitions functions and outputs at the zero level. These combinations can then be reduced to functions or relatively finite automata FA_s^i of higher levels (Fig. 2). As a result, a multilevel relatively finite automata, as a model of the observed object, is obtained. Note that this automata is relative to the time interval at which events are analyzed. With the receipt of new information about the observed object, the model of the automata may change.

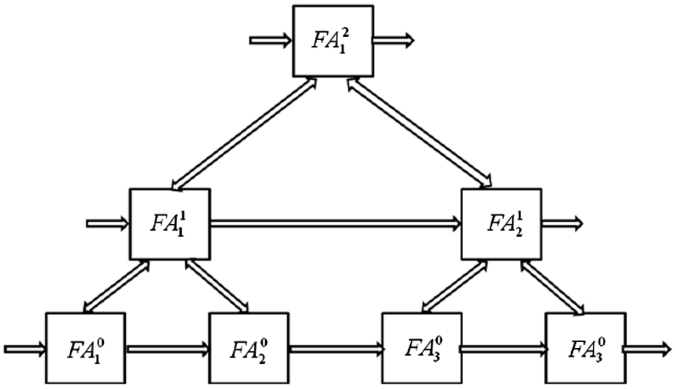

Fig. 2. An example of the structure of three-level relatively finite automata

For the rapid search for stable combinations of possible transition functions for MRFA, special algorithms are applicable.

To assess the completeness of the synthesized multilevel relatively finite automata, the formulas given in the previous section are applicable.

4.2 Algorithm of Deductive Multilevel Synthesis

Deductive synthesis algorithm allows build dynamic models of the observed objects, which reflect changes in objects states in time. To do this, the algorithm links the constructed MRFA into a single dynamic structure. These structures are dynamic models of observed objects.

The presence of levels in the structure of the MRFA allows split the data into groups that form a hierarchy. The peculiarity of the deductive synthesis problem is that the transition from the target state to the final state involves the synthesis of models on many levels.

In the initial formulation of a single-level synthesis, it is assumed that the initial data $\{d_s\}$ and the final result $\{d_w\}$ which is to be achieved are given. Conditions (rules) connecting the initial state with the final state are defined as $F_{zv}(d_{zv_e}; e = \overline{1, E_z}) \to d_{zv_a}; z = \overline{1, Z}; v = \overline{1, V_z}$. It is necessary to synthesize a process that allows make the transition $\{d_s\} \to \{d_w\}$. In this case, the desired PRG process can be represented as: $PRG = \left\{F_{zv}(d_{zv_e}; e = \overline{1, E_z}) \to d_{zv_a}; \{d_s\}; \{d_w\}; z = \overline{1, Z}; v = \overline{1, V_z}\right\}$.

If predicates $P_{zv0}(F_{zv0}(\cdot))$, $P_{zv1}(d_{zv1})$, …, $P_{zva}(d_{zva})$ that take value 1 are defined for the elements, when the variables are defined (true), and 0 otherwise, the conditions of the problem can be written as $\{P_{zv0} \wedge P_{zv1} \wedge, \ \ldots, \ P_{ZVE_z} \to P_{zva} | S_{zv}, \ M_{zv}, \ z = \overline{1, Z} : v = \overline{1, V}\}$, where S_{zv} - status of zv - the condition; M_{zv} - the set of numbers of the basic conditions under which the preconditions and post conditions are true and false respectively.

In the new formulation of the synthesis problem the initial data $\{d_s\}$ are divided into data groups $\{d_{w0}\}$, $\{d_{w1}\}$, …, $\{d_{wi}\}$, …, $\{d_{wK}\}$, correlated with the corresponding levels of hierarchy. Conditions $F^i_{zv}(d^i_{zv_e}; e = \overline{1, E_z}) \to d^i_{zv_a}; z = \overline{1, Z_i}; v = \overline{1, V_{iz}}; i = \overline{1, K}$ connecting the source data with the final result are determined, where $F^i_{zv}(\cdot)$ - functions of z-types and v-types that can be implemented by the process at the i-th level of the hierarchy; $d^i_{zv_e}, d^i_{zv_e}$ - data; K - number of hierarchy levels. At the same time, restrictions are placed on functions and data at the i-th level: $F^i_{zv}(\cdot) \in FB^i$; $d_{si}, d^i_{zv_e}, d^i_{zv_a}, d_{wi} \in D_i$; $i = \overline{1, K}$, where FB^i, D_i - the set of admissible functions and the set of admissible data at the i-th level. It is required to synthesize a process that allows move from the source data $\{d_s\}$ to result $\{d_w\}$ taking into account the conditions considered.

With such a statement of the problem, it is proposed to carry out the synthesis of models on the base of functions belonging to different levels of the hierarchy. The proposed algorithm for solving the problem can be represented as a sequence of eleven steps:

1. First, $i = K + 1$.
2. $i = i - 1$. Decrease the hierarchy level.
3. If $i < 0$, then the completion of the solution of the problem with achieving a positive or negative result.
4. Appeal to the conditions of the problem at the i-th level.
5. Proof of the existence of a process to move from $\{d_{si}\}$ to $\{d_{wi}\}$ with effectiveness not lower than specified for the i-th level. The proof is based on the rules connecting the initial state to the final one. In all cases, the storage of proved and unproved results at this level of the hierarchy is carried out and added, respectively, to the source data and to the final result at a level lower than the current one.
6. In the absence of such proof, go to step 2.
7. Extract the support process from the results of the proof.
8. If there are no logical conditions in the support process, then go to step 11.

9. Process logical conditions, get subprocesses.
10. Bring the subprocesses together into a general process at the *i*-th level.
11. Check the ability to reach $\{d_{wi}\}$ using the results of the synthesis process at considered levels. Upon the positive result, the processes synthesized at each level are consolidated into the resulting process. The end of the algorithm. In other cases, go to step 2.

To extract the process from the proof the idea of the reverse conclusion is used. Through the reverse conclusion symmetrically to the direct output, it is possible to build a process that does not contain unnecessary elements.

With this approach, the synthesis of models is reduced to solving a small number $k \leq K$ of simple problems. They are supposed to be solved starting from the top level problem. A low complexity of each problem is determined by a small number of analyzed conditions. When solving a problem at the *K*-th level, a rough synthesis from large blocks of functions is carried out. In this case, it is not required to strictly prove the possibility of transition from $\{d_{sK}\}$ to $\{d_{wK}\}$. Inconsistencies of $\{d_{wK}\}$ and output of the conclusion at this level are taken into account at corrective synthesis within lower levels of the hierarchy.

In contrast to the known methods, the proposed solution can significantly reduce the time complexity of automatic synthesis. The upper bound of time T_H can be defined as $T_H \approx c\sum_{i=1}^{K} m_i^2 \leq c(\sum_{i=1}^{K} m_i)^2$, where c is a constant coefficient; m_i - the number of conditions of the problem at the *i*-th level. Notice, that m_i is significantly less than the total number of conditions on which problems of program synthesis are solved by traditional methods. This estimate is valid when the number of conditions for multilevel and single-level synthesis problems is the same. Taking into account that at each top level, one step of output is equivalent to n_i steps at the level "0", it is possible to estimate a lower bound for the time T_L of multilevel program synthesis: $T_L \approx c\sum_{i=0}^{K} \frac{m_i^2}{n_i^2} \leq c\sum_{i=0}^{K} m_i^2$, where n_i - the number of elements of the *i*-th level relatively to the base level.

5 Technology of Multilevel Synthesis for Biological Systems

Let's consider specific features of multilevel synthesis of models of biological systems. Such synthesis allows build models of the complex biological systems. The inductive synthesis of biological models is based on processing values of the observed parameters. Let a system is characterized by *N* parameters which are measured through some time intervals.

Let's define the moments of measurements as reference points and distinguish them with the help of indexes. Taking into account limitation of the period of observation, the number of reference points is limited. As a result of measurements we receive the time series which reflects behavior of the system. The number of elements of each time series is equal to number of reference points. If observed data contain noise, emissions, missed values, then a preprocessing of time series is carried out.

The algorithm of model synthesis may include any number of steps. For the description of technology we will limit the number of steps and we will consider technology of three-step synthesis. On the first step of synthesis functions for calculation of integrated indicators are defined. They are calculated for separate groups of parameters. Groups of parameters are formed from an initial set of parameters. Integrated indicators characterize states of the biological system in fixed moments of time, which correspond to reference points. On the second step of synthesis the integral curves which reflect changes of indicators in time are constructed.

The third step of synthesis assumes creation of the functions providing the joint analysis of the calculated integrated indicators and construction on their basis of the resulting assessment of the biological system state. This assessment is constructed on the basis of the results of comparison of integral curves behavior.

The steps of the process of the inductive synthesis in details are described below.

Creation of integrated indicators for groups of input data (F_0, F_1) for the fixed moment of time t_j:

$$\underbrace{BioM[t_j]}_{\text{static model}}: \underbrace{\left\{\begin{array}{c} param_1\ [t_i; t_j] \\ param_2\ [t_i; t_j] \\ param_3\ [t_i; t_j] \\ \cdots \\ param_{N-1}\ [t_i; t_j] \\ param_N\ [t_i; t_j] \end{array}\right\}}_{\text{parameters}} \overset{F0}{\Rightarrow} \underbrace{\left\{\begin{array}{c} gr_1\ (t_j, param\ (\cdot)) \\ gr_2\ (t_j, param\ (\cdot)) \\ \cdots \\ gr_M\ (t_j, param\ (\cdot)) \end{array}\right\}}_{\text{groups of parameters}} \overset{F1}{\Rightarrow} \underbrace{\left\{\begin{array}{c} ind_1\ (t_j, gr\ 1) \\ ind_2\ (t_j, gr\ 1) \\ \cdots \\ ind_M\ (t_j, gr\ M) \end{array}\right\}}_{\text{integral indicators}},$$

where *param* - is a parameter, *gr* - is a group of parameters, *ind* - is an integrated indicator calculated for a group of parameters. Creation of integral curves from values of indicators (F_2) and identification of dependences in their behavior (F_3) for time interval $[t_i, t_j]$:

$$\underbrace{BioM[t_i, t_j]}_{\text{dynamic model}}: \underbrace{\left\{\begin{array}{c} BioM[t_i] \\ BioM[t_{i+1}] \\ \cdots \\ BioM[t_j] \end{array}\right\}}_{\text{static models}} \overset{F2}{\Rightarrow} \underbrace{\left\{\begin{array}{c} curve_1([t_i, t_j], ind_1\ (\cdot)) \\ curve_2([t_i, t_j], ind_2\ (\cdot)) \\ \cdots \\ curve_M([t_i, t_j], ind_M\ (\cdot)) \end{array}\right\}}_{\text{integral curves}} \overset{F3}{\Rightarrow} \underbrace{\left\{\begin{array}{c} G_1\ ([t_i, t_j],\ curve(\cdot)) \\ G_2\ ([t_i, t_j],\ curve(\cdot)) \\ \cdots \\ G_L\ ([t_i, t_j],\ curve(\cdot)) \end{array}\right\}}_{\text{relations between curves}}$$

where *curve* - is an integral curve constructed on the base of separate values of indicators; *G* - dependence in behavior of two or several integrated curves.

Functions F_0, F_1, F_2,F_3 link models elements. So, F_0 links parameters of one group, F_1 - defines linked sequence of transformations which allow pass to integrated indicators, F_2 links separate values of indicators.

Functions $F_0 - F_3$ uniquely define the automata model shown in Fig. 2. In the process of automata model synthesis F_0 is used on the zero level, F_1 is used on the first level, F_2 on the second level, etc. Thus, creation of the functional model of the

automata comes down to finding of compliances of elements of automata structural levels and the functions F received as a result of the inductive synthesis: $FA^0 \leftrightarrow F_0$; $FA^1 \leftrightarrow F_1$; $FA^2 \leftrightarrow F_2$; $FA^3 \leftrightarrow F_3$

The state of a biological system Q is defined by a set of links which exist in a system. The structure of links is considered and estimated for some fixed moment of time t_j. In the subsequent and previous periods of time there can be other links which are different from observed at the current moment of time. Also, absolute values of parameters and the counted indicators are dependent on time.

In a system ratios of changes in behavior of integral curves are invariant in time. In behavior of curves the invariance of dependences in behavior of initial parameters is the cornerstone of an invariance of dependences.

Thus, for some *k-th* state of a biological system Q_k are fair the following ratios. The state of a system depends upon time: $Q_k[t_i] \neq Q_k[t_j]$, $i \neq j$. At the same time we assume that the relations between observed parameters are constant: $F[Q_k[t_j]] = F[Q_k[t_i]]$, $\forall\, i, j$. The considered properties of systems are used for assessment of their states on the basis of deductive synthesis.

Deductive synthesis assumes that the goal presents, for example, to estimate an object state in certain moment of time t_w, i.e. $Q[t_w]$ is defined.

As an input we have results of parameters measurements for the previous moments of time t_s: t_w: $s \leq w$. Using built earlier automata model one can proof existence of the transition $FA^3[t_s] \rightarrow FA^3[t_w] = Q[t_w]$.

In the process of transition a number of the intermediate steps can be carried out: $FA^3[t_s] \rightarrow \ldots FA^3[t_k] \rightarrow \ldots \rightarrow FA^3[t_w]$.

In our case the proof at first is carried out on top level (the third level). If it is feasible, then the goal is achieved, and it takes only small number of steps. If a part of links is absent, then for their restitution transition to the second level is carried out and so on. Transitions to lower levels are carried out until links, necessary for the proof, is reestablished or the zero level is reached. In the limiting case when transitions to a zero level are carried out on each step, the sequence of transitions can be defined as:

$$\rightarrow FA^3[Q] \rightarrow \left\{ \begin{array}{c} FA^2[t_s] \rightarrow FA^1[t_s] \rightarrow FA^0[t_s] \rightarrow FA^1[t_s] \rightarrow FA^2[t_s] \\ FA^2[t_j] \rightarrow FA^1[t_j] \rightarrow FA^0[t_j] \rightarrow FA^1[t_j] \rightarrow FA^2[t_j] \\ \ldots \\ FA^2[t_w] \rightarrow FA^1[t_w] \rightarrow FA^0[t_w] \rightarrow FA^1[t_w] \rightarrow FA^2[t_w] \end{array} \right\} \rightarrow FA^3[Q_k[t_w]] \rightarrow$$

In the given example as a result of the proof it is established that in an instant of time t_w the system is in a state Q_k.

6 Simulation Results for Biological Systems

The considered technology was used to assess the state of patients with c surgical pathology in a cavernous sinus during the postoperative period in the operating room and in the cardio-resuscitation unit. The assessment of the patients' state was carried

out at six time control points. The assessment included an analysis of the parameters characterizing the acid-base state (ABS) of the organism. The total number of such parameters was twenty one. These were the following parameters: pH – Acidity, pO2 - Oxygen partial pressure, pCO2 - Carbon dioxide partial pressure, ABE - Excess base, SBE - Lack of reason, cHCO3 - Plasma bicarbonate, cHCO3-st - Bicarbonate (alkali), sO2 - Oxygen boost, ctHb - Reference hemoglobin level, Htc – Hematocrit, K+ - Potassium ion concentration, Na+ - Sodium ion concentration, Ca++ - Calcium ion concentration, Cl− - Chlorine Ion Concentration, Glu - Glucose concentration, Lac - Lactate content, p50 - Hemoglobin affinity for oxygen, mOsm - Blood osmolarity, pH (T) - Acidity corrected for temperature, pO2(T) - Partial oxygen pressure adjusted for temperature, pCO2(T) - Carbon dioxide partial pressure adjusted for temperature.

It is known that when assessing the state of patients by medical specialists, the values of individual measured parameters, the dynamics of their changes are analyzed. However, the focus is on the study of the consistency and synergies of the behavior of various parameters. The behavior of parameters is considered consistent if the ratio of their values is as expected. The expected dependencies are determined by the nature of the parameters. The importance of analyzing coherence and synergy is justified by the fact that the organism is a unified system, within which all processes are connected.

As a consequence, the violation of one process should lead to the violation of other processes. The absence of such cause-effect relationships indicates a violation of one of the main properties of all living organisms - the integrity property. In this case, the organism loses its ability to adapt and ability to self-healing.

The analysis of dependencies of many parameters in dynamics is a complex task that requires in-depth analysis. Some of the modern medical information systems involve the use of separate methods of artificial intelligence, including the methods of Data Mining. However, methods based on direct iteration are not applicable due to the large amount of data being processed, while others can lead to a significant loss of information. In addition, well-known methods do not always allow the formation of capacious structures reflecting the dynamically changing relationships of individual parameters and groups of parameters.

Such problems are successfully solved using the proposed models and methods of multilevel synthesis. They provide the construction of multilevel models describing the state of the organism and changes occurring in it at fixed points in time and relative to the entire time period that is considered.

In the synthesis of patient state models, the features of working with medical data were taken into account through the use of criteria and indicators proposed in specialized medical methods, in particular, by Anokhin [20], Lushnov et al. [21].

Let's consider data on three groups of patients. In the formation of groups, the main diagnosis was taken into account, as well as other characteristics that influence the state of patients. These characteristics are the patient's age, associated diseases and others. For each patient, the values of ABS parameters, measured at six control points, were included in the sample. The measured data contained missing values. To fill them, the KNN (K-Nearest Neighbors) method was applied.

The data prepared in this way were used to synthesize models of patient status. According to the technology, the following steps were performed.

1. Calculation of functionals of biosystems. Search of splitting $R = (R_1, R_2, ..., R_M)$ sets of objects (parameters of ABC) on not crossed classes are sets of the functional subsystem of parameters of ABC: $R_1, R_2, ..., R_M$ ($M = 1$ or $M > 1$), which gives local maximum to F the sum of "internal" correlation links minus some threshold value of correlations characterizing their importance:$F(a, R) = \sum_{S=1}^{M} \sum_{i,j \in R_S} (a_{ij} - a)$ where a—a threshold of importance of links (at $a_{ij} > a$ the link is stronger between objects i and *at* $a_{ij} < a$—the link is insignificant), a_{ij}—is an indicator of link between *i-th* and *j-th* objects ($a_{ij} = a_{ji}$, a_{ii}—aren't investigated and aren't considered) expression $i, j \in R_S$ means *aij* element belonging to a set of R_S [22].
2. Construction of integral curves based on calculated values of functionals and thresholds of the essence of links. Formation of a matrix of partitioning into non-intersecting classes of parameters of ABS.
3. Investigation of the consistency of the behavior of functionals, the thresholds of the essence of links and changes in the number of disjoint classes.
4. The formation of dependencies characterizing the state of patients in each group.

Below are the results of a study of data about patients in the first group. The dynamics of system correlation and the corresponding changes in cooperative correlation relationships between many indicators of the acid-base state in this group of patients are given in Fig. 3 and in Tables 1 and 2.

From the Fig. 3 it can be seen that the threshold of essence of links demonstrates substantial stability in the period from the 1st to the 5th point within the limits of 0.45–0.49. However, by the 6th point it rises sharply to a value of 0.654. In this case, the number of partitioning classes increases from 5–7 classes from the 1st to the 5th point to 10 at the 6th point of the study. According to the results of Table 2, the transition from the 5th to the 6th point of the study can be assessed as the most "stressful" of the moments in the system, because at this time there is a "decay" of the set of parameters of the ABS into 10 non-overlapping classes with a sharp increase in the threshold of materiality of the links 1.4 times from a value of 0.462 to 0.654.

Table 1. Indicators of functionals, thresholds of essence of links and the number of classes of splitting ABS cavernous sinus in the 1st group

Point of study	Functional	Thresholds of links	Number of classes
1	35,794	0,457	5
2	32,341	0,455	6
3	24,975	0,432	5
4	27,221	0,488	7
5	39,753	0,462	5
6	21,355	0,654	10

Thus, at the end of the study in group 1 to the 6th point, the system seemed to "crumble" - the number of partitioning classes increased to 10, the threshold of essence

Table 2. Splitting into non-intersecting classes of parameters of ABS in cavernous sinus in the 1st group

	Point_1	Point_2	Point_3	Point_4	Point_5	Point_6
Klass1	pH(T) cHCO3-st SBE ABE pH	pCO2(T) pH(T) mOsm p50 Ca++ Na+ K+ Htc ctHb	pO2(T) pH(T) Lac Cl- Htc ctHb sO2 pO2 pH	pH(T) Glu Htc ctHb cHCO3-st cHCO3 SBE ABE pH	pCO2(T) pH(T) p50 Lac Cl- K+ Htc ctHb cHCO3-	pH(T) cHCO3-st cHCO3 SBE ABE pH
Klass2	pO2(T) sO2 pO2	pO2(T) sO2 pO2	pCO2 (T) p50 pCO2	pO2(T) sO2 pO2	pO2(T) sO2 pO2	pO2(T) sO2 pO2
Klass3	pCO2(T) mOsm p50 Lac Glu Cl- Ca++ Na+ Htc ct	cHCO3-st cHCO3 SBE ABE	K+ cHCO3-st cHCO3 SBE ABE	pCO2(T) p50 Lac pCO2	mOsm Na+	pCO2(T) Cl- pCO2
Klass4	cHCO3	Cl-	mOsm Na+	K+	Ca++	Htc ctHb
Klass5	K+	Glu	Glu Ca++	mOsm Na+	Glu	K+
Klass6		Lac		Ca++		mOsm Na+
Klass7				Cl-		Ca++
Klass8						Glu
Klass9						Lac
Klass10						p50

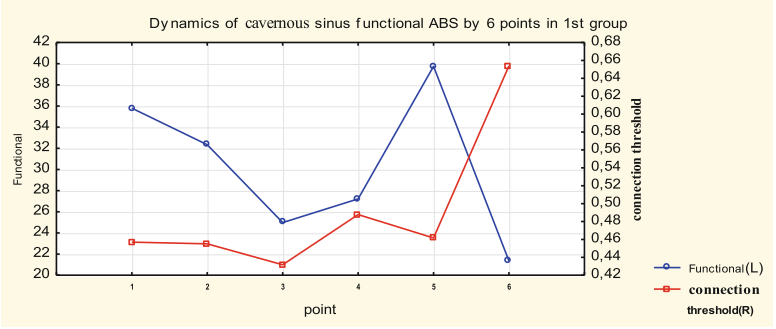

Fig. 3. Dynamics of functionals and thresholds of essence of links between ABS parameters in the cavernous sinus in the 1st group

of links increased to 0.654, and the functional in turn dropped to the minimum value -21.355 from 39.753, those almost 2 times (1.86). According to the work of Teodorescu et al. [23] here the "critical period" is also observed, since in the period between the 5th and 6th points the ratio of the subsequent value of the functional to the previous one is minimal.

Similar studies were conducted for patients of other two groups. As a result, the following dependencies were identified that determine the state of the patients of the three studied groups.

1. The maximum shifts in the system of ABS parameters in the cavernous sinus of the 1st group of patients occur in the period between the 5th and 6th points of the study.
2. The maximum shifts in the system of ABS parameters in the cavernous sinus of the 2nd group of patients also occur in the period between the 5th and 6th points of the study, but variations in the values of both the significance thresholds of the links and the values of the functionals in the 2nd group are significantly higher than in the first group. In other words, the 2nd group has a more unstable dynamics of ABS parameters.
3. The 3rd group of subjects has relatively the smallest variations of the studied parameters.

When working with data on new patients, the identified dependencies will allow assess the patient's condition and promptly identify deviations from the expected in case of violation of one or several dependencies.

7 Conclusion

In this article the problem of multilevel automatic synthesis of the models of complex objects is discussed. A new problem statement for synthesis is given. The structure of the process of automatic construction of these models, including data acquisition, processing and direct synthesis of the corresponding automata is considered. To formalize the observed objects it is suggested to use relatively finite operational automata. The necessity of transition from single-level automata models to multilevel structures is shown. The features of multilevel relatively finite automata and the criteria for the efficiency of their synthesis are determined. It is proposed to use the completeness of the automata description and the time of its construction as the main criteria of efficiency.

It is envisaged that the synthesis of MRFA of observed objects should be carried out according to the proposed methods and algorithms. A new method, based on combined use of inductive and deductive approaches to the synthesis is proposed. A distinctive feature of the method is its ability to synthesize multilevel models of observed objects. The algorithm of multilevel inductive synthesis, which is a part of the method, allows build automata models on limited time intervals when objects are observed. A new multi-level deductive synthesis algorithm provides linking of the constructed automata models into dynamic structures, that reflect changes in the states of objects over time intervals.

The proposed method makes it possible to significantly reduce the time spent on the synthesis of observed objects models. This is achieved by solving the problem of synthesis on many levels. At each level, its own tasks are formulated and solved. The overall problem is reduced to a small number of simple tasks. Estimates of the complexity of the proposed multilevel synthesis method are obtained.

The results of simulation show that the proposed new solutions for the automatic synthesis of multilevel automata models allow build models of such complicated objects as biological objects.

It is necessary to notice that use of the offered synthesis algorithms of multilevel automata models isn't limited to medical domain. Now authors consider the possibility of use of this approach for creation of models of the complex natural systems for which description automatic models weren't used earlier [24–26]. Results of preliminary researches show that under certain conditions this approach can be useful, especially when multi model approach is used.

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