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## ONLINE MEDICAL DATA STREAM MINING BASED ON ADAPTIVE NEURO-FUZZY APPROACHES


***Introduction.*** *Data mining approaches in medical diagnostics tasks have a number of special properties that do not allow the use of such approaches in a classical form. That's why adaptive neuro-fuzzy systems for online medical data stream processing tasks and its learning algorithms have been developed. Proposed systems can process medical data streams in three modes: supervised learning, unsupervised learning and active learning.*

***The purpose*** *of the paper is to develop approach, based on adaptive neuro-fuzzy systems to solve the tasks of medical data stream mining in online-mode.*

***Methods.*** *The methods of computational intelligence are used for medical data stream processing and, first of all, artificial neural networks, neuro-fuzzy systems, neo-fuzzy systems, their supervised, unsupervised and active learning approaches, gradient methods of optimization, methods of evolving system.*

***Results.*** *As a result, approbation of the developed approach in supervised learning mode using multidimensional neo-fuzzy neuron on medical data of patients with urological disease was investigated. Percentage of errors in system testingusing all feature space is 11.11 %, using the most informative features the error rate becomes 6.4 %. Also multidimensional neo-fuzzy neuron was used for diagnostic of the pharmacoresistant form of epilepsy, percentage of errors in system testing is 5.82 %. Approval of the developed approach in the mode of active training and association on the data of patients with pulmonary diseases was performed. For all approbation results performance criterion was calculated, its values are suitable for the tasks of medical diagnostics in data stream mode.*

***Conclusions.*** *The proposed neuro-fuzzy approaches allow obtaining additional information about patients diagnosis in conditions of limited a priori information about patient.*



***Keywords:*** *adaptive system, neuro-fuzzy system, medical data mining, medical data stream.*

## INTRODUCTION

Currently, data mining approaches are widely used to solve a wide range of problems in industry, economics, finance, banking, agriculture etc. In the area of medical diagnostics these methods are called medical data mining approaches [1-4]. The specialty of this area is the inability to use the traditional methods of data mining in its pure form, which is associated with a number of circumstances:

- limited sampling to be classified;
- significant overlapping of classes related to various diseases;
- nonlinear nature of hypersurfaces that divide these classes;
- the presence of anomalous observations that can distort primary information;
- a significant role of the subjective human factor that does not provide accurate data;
- a need to process medical data sequentially in online mode;
- an ability to present medical data in the form of data streams.

All of these circumstances lead to the formation of non-convex and blurred classes, for which the suitable mathematical methods are methods of computational intelligence, above all, artificial neural networks, fuzzy inference systems and hybrid neuro-fuzzy systems. However, the systems listed are not a «panacea» in the tasks of medical diagnostic because they require large amounts of information for their training, which are often not available to physicians and are not adapted to the need to process data in a sequential online mode. It should also be emphasized that the compulsory stage is the preparation of medical data, covering the task of filling in missing values (if any), normalizing the data and reducing the number of features by compressing the data or selecting the most informative features. The available approaches do not ensure compliance with these online requirements for medical diagnostic tasks.

The eHealth system was introduced in Ukraine in 2018, with the ultimate goal of creating a database of medical records for all Ukrainians by 2020. At this stage, the processing of medical information in sequential mode using the medical data mining approaches will be relevant. The main tasks in this area are the problems of diagnosis, which are solved by means of pattern recognition based on paradigms of supervised learning and unsupervised one (self-learning), and they are reduced to solving problems of classification or clustering.

The goal of this work is to improve the effectiveness of medical diagnostics in online mode based on the intellectual analysis of medical datasets using hybrid neuro-fuzzy systems in conditions of limited a priori information about patient.

## DATA STREAM PROCESSING

High-dimensional medical data form data streams — sequential feeding to processing at short time intervals. That is why all the approaches used to processing and analyzing such datasets must be adapted to sequential data stream processing. An example is the formation of a data streaming one of the departments of a hospital or one hospital as a whole, when different physicians form separate data about each patient and these data are sent to the central repository or hospital database. Thereafter, medical data from all hospitals are transferred to the eHealth Repository (Fig. 1).

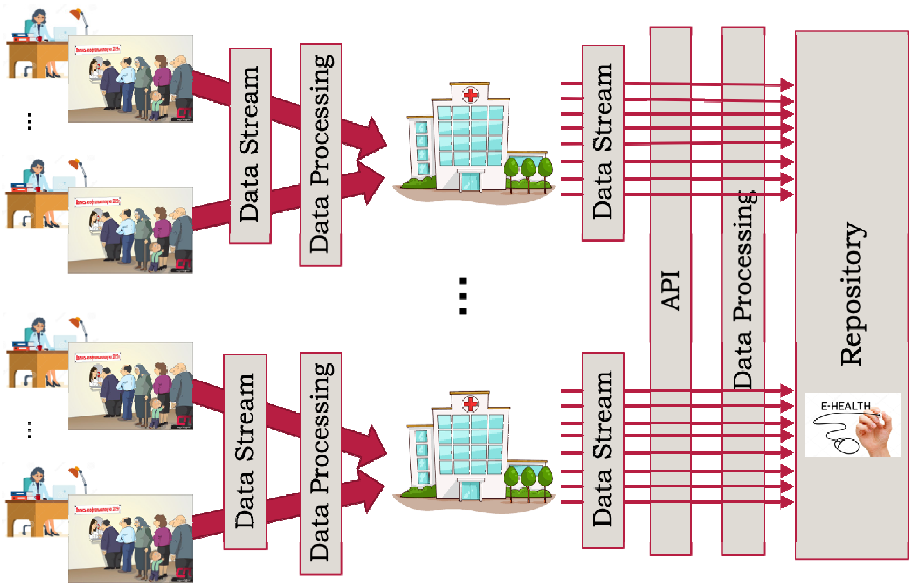


***Fig. 1.*** Medical Data Stream

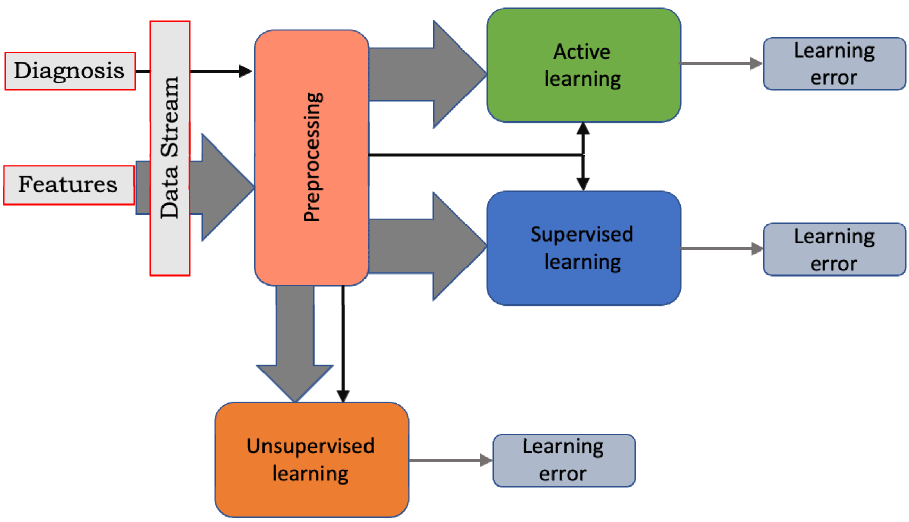


***Fig. 2.*** System training process

It is understandable that data stream characteristics (such as density and time between patients) in a single hospital department will be less than those ones in the entire hospital and country.

Medical data stream processing should be performed in several steps, which depends on ability to know the diagnosis $d_j$ of a sufficient number of patients to form training set for using supervised learning approaches or using unsupervised or active learning methods in other cases. The use of the mentioned approaches requires different initial data, depending on whether the system is trained or tested (Fig. 2, Fig.3).

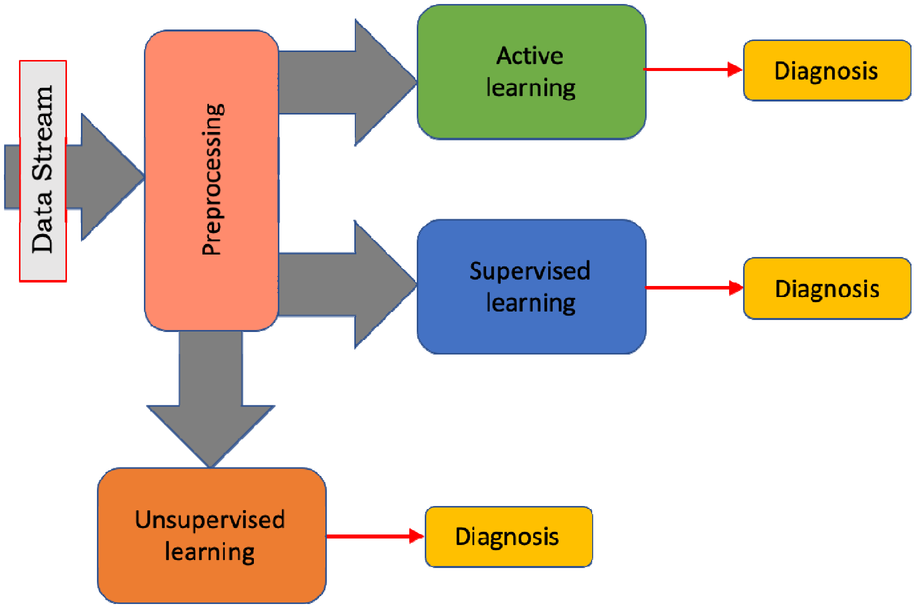


***Fig. 3.*** System testing process

At first we need to find out input data characteristics such as parameters of one element of data stream, formed by $N$ $n-$dimensional feature vectors

$$X=\{x(1),x(2),...,x(N)\}, \tag{1}$$

where $x(k)\in X$; $k=1,2,...,N$; $N$ — total number of patients; $n$ — total number of features for each patient.

In our case each element is a sample of observations

$$x(k)=(x_1(k),x_2(k),...x_i(k),...,x_n(k))^T\rightarrow d_j(k). \tag{2}$$

Further analysis assumes a fuzzy partitioning of the original dataset into $m$ classes with some level of membership of $k-$th vector to the $j-$th cluster class (diagnosis) $d_j(k)$.

## DATA PREPROCESSING STAGE

In the medical data stream mining tasks, the data of biomedical research are collected from different sources (different hospitals, hospital departments, etc.). That is why there is a problem of the absence of clearly defined parameters of the organism, which were measured for a particular nosology. This problem is expressed in gaps in the patient's features, in the presence of which it is not possible to process the whole table without filling them in advance. Approaches for filling gaps was described in [5-6], for its online version adapted for medical data processing see [7]. During data stream processing, the gaps will be filled in such a way that the recovered elements would in some sense be most "similar" or "close" to the a priori unknown patterns hidden in this table by improving the method of spatial extrapolation (Fig.4) [8]. To fill gaps in the features of patient $x(k)$ at first we need to calculate the partial distances $dist(k,p)$ between $x(k)$ and all other patients $x(p)$, $k \neq p$ using formula

$$dist(k,p)=\frac{1}{n-g_k-g_p+g_{kp}}\sum_{i=1}^{n}\left|x_i(k)-x_i(p)\right|, \quad (3)$$

where $g_k$, $g_p$ — number of gaps in the features of $k$-th and $p$-th patient, $g_{kp}$ — number of gaps in common features of $k$-th and $p$-th patient.

Using partial distances values $dist(k,p)$ we can calculate membership function $mu(k,p)$:

$$mu(k,p)=\frac{dist^{-1}(k,p)}{\sum_{p=1}^{N-1} dist^{-1}(k,p)}. \quad (4)$$

At the final stage a gap value is filled using formula:

$$x_{\tilde{i}}(k)=\sum_{p=1}^{N-1} mu(k,p)\cdot x_{\tilde{i}}(p), \quad (5)$$

where $x_{\tilde{i}}(p)$ does not contain a gap.

After filling all gaps online medical data preprocessing tasks require to calculate basic sample statistics such as mean, variance, extreme values (maximum and minimum) also sequentially without the need for accumulating data [9].This step allows you to normalize the data stream to the necessary interval $[-1;1]^n$ or $[0;1]^n$ in online mode.

A final stage of data stream preprocessing is a step of feature selection-extraction. The need for such processing is due to the fact that medical datasets often contain too many features with a small number of patients, which significantly limits the possibilities of existing methods for further diagnosis. In order to select the most informative features from the available feature space, it is proposed to integrate the advantages of systems based on the combination of methods of compression of the original features space with the methods of finding the most informative features and to create a single adaptive hybrid method of evaluating the informativeness of features with the selection of the most informative ones [10–11]. A hybrid method of evaluating the informativeness of medical features is presented in Fig. 5.

It consists of a block of normalization and centering of input features, a block of calculating of first principal component using a modified Oja neuron [12-15], a block of definition of the "feature-winner" where a feature with minimal distance to the first principal component is defined.The distance in the sense of the Manhattan metric is calculated according to:

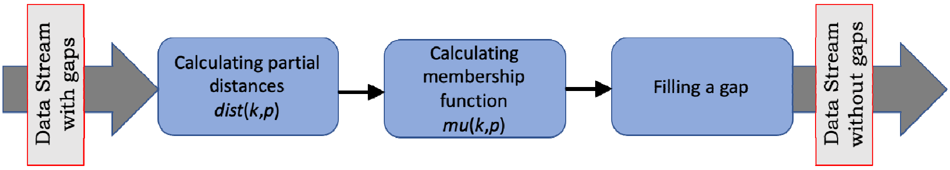


***Fig. 4.*** Process of filling the missed values

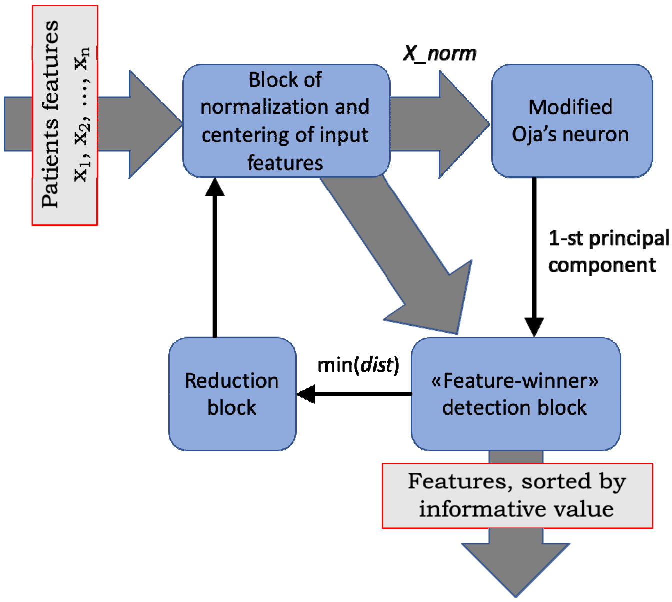


***Fig. 5.*** Feature selection-extraction approach

$$dist\left(x\_norm(z), pr\_comp^{(1)}\right) = \sum_{i=1}^{N} \left| x\_norm_i(z) - pr\_comp^{(1)} \right| \qquad (6)$$

in the reduction block, "feature-winner" is removed and the next informative feature begins to be searched.

## SUPERVISED LEARNING MODE

Medical data mining approaches in a supervised learning mode based on adaptive hybrid neuro-fuzzy systems are appropriate to use in situations where there is a representative training sample that means that diagnosis of many patients is known. The first method in this approach is to modify a multidimensional neo-fuzzy-neuron (Fig. 6) [16–17].

Triangular structures are usually used as a membership function $\mu_{li}(x_i)$, its value is determined by the distance between the value of the input feature $x_i$ and the centers of these functions $c_{li}$. So the output of this layer can be presented in the form:

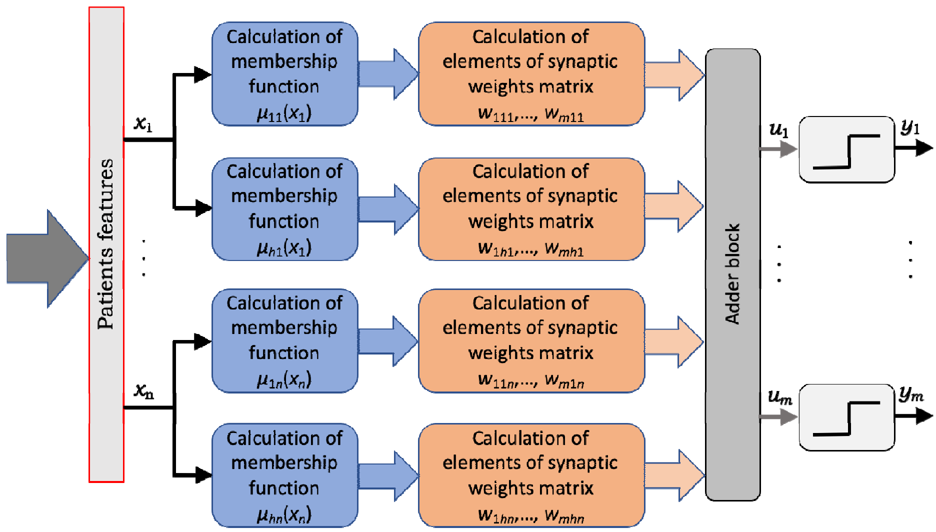


***Fig. 6.*** Multidimensional neo-fuzzy-neuron

$$\mu(k)=\left(\mu_{11}(x_1(k)),\mu_{21}(x_1(k)),\ldots,\mu_{h1}(x_1(k)),\ldots\mu_{hn}(x_n(k))\right)^T . \tag{7}$$

The signal at the output of the neo-fuzzy-neuron can be calculated as:

$$u(k)=W(k)\mu(k),\, y(k)=\text{sign}\, u(k), \tag{8}$$

where $W(k)=\begin{pmatrix} w_{111}(k),\ldots, & w_{1h1}(k),\ldots, & w_{1li}(k),\ldots, & w_{1hn}(k) \\ w_{211}(k),\ldots, & w_{2h1}(k),\ldots, & w_{2li}(k),\ldots, & w_{2hn}(k) \\ \vdots\in & & & \\ w_{m11}(k),\ldots, & w_{mh1}(k),\ldots, & w_{mli}(k),\ldots, & w_{mhn}(k) \end{pmatrix}$ — synaptic weights matrix, customizable using a modified procedure [18]

$$\begin{cases} W(k+1)=W(k)+r^{-1}(k)\left(d(k)-\text{sign}\ W(k)\mu(k)\right)\mu^T(k), \\ r(k)=\alpha r^{-1}(k-1)+\|\mu(k)\|^2, \quad 0\le\alpha\le 1 \end{cases} \tag{9}$$

that optimizes the learning criterion

$$E_j(k)=\frac{1}{2}e_j^2(k)=\frac{1}{2}\left(d_j(k)-y_j(k)\right)^2 . \tag{10}$$

To enhance the capabilities of Medical Data Mining approaches in supervised learning mode, a hybrid neuro-fuzzy system (HNFS) has been provided [19] (Fig.7). A particularity of this system is the ability to further change its architecture in situation when number of features or diagnosis can be changed [19–21].The normalized feature vector is fed to the input layer of the HNFS, that consists of $nh$ membership functions $\mu_{li}(x_i(k))$ and performs the fuzzyfication of feature vector:

$$\mu_{li}(x_i(k)) = \exp\left(-\frac{(x_i(k)-c_{li})^2}{2\sigma_i^2}\right), \tag{11}$$

where $c_{li}$ — center of membership function, $\sigma_i$ — width of membership function.

At the output of multiplication block values $\prod_{i=1}^{n}\mu_{li}(x_i(k))$ have been calculated. After we perform tuning of synaptic weights matrix, adder blocks (AB) calculate signals:

$$\tilde{x}_j(k) = \sum_{l=1}^{h} w_{jl} \prod_{i=1}^{n} \mu_{li}(x_i(k)). \tag{12}$$

In Rectified Linear Unit (ReLU) block calculates [22]:

$$\varphi(\tilde{x}_j(k)) = \begin{cases} \tilde{x}_j(k), & \text{if } \tilde{x}_j(k) > 0, \\ 0, & \text{if } \tilde{x}_j(k) \le 0. \end{cases} \quad j = 1,2,\ldots,m, \tag{13}$$

which are transformed in normalizing block using adder block (AB) value $\sum_{l=1}^{h}\prod_{i=1}^{n}\mu_{li}(x_i(k))$ and provide calculating of $u_j(k)$:

$$u_j(k) = \frac{\varphi\left(\sum_{l=1}^{h} w_{jl} \prod_{i=1}^{n} \mu_{li}(x_i(k))\right)}{\sum_{j=1}^{m} \varphi\left(\sum_{l=1}^{h} w_{jl} \prod_{i=1}^{n} \mu_{li}(x_i(k))\right)}. \tag{14}$$

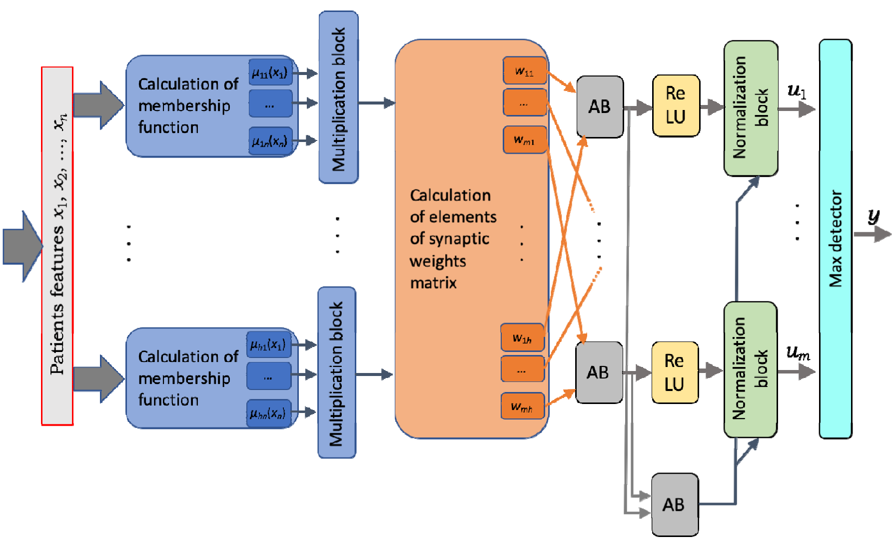


***Fig. 7.*** Hybrid neuro-fuzzy system (HNFS)

Output signal of HNFS is calculated using maximum detector:

$$y(k) = \max\{u_1, u_2, ..., u_m\}. \tag{15}$$

Learning criterion for training proposed system can be presented in the form [22]:

$$E_j(k) = \frac{1}{2}\left\| d(k) - \tilde{x}(k) \right\|^2. \tag{16}$$

Modificated procedure that is used for tuning of synaptic weights matrix has been written in the form:

$$W(k+1) = W(k) + \frac{e(k)\left(\prod_{i=1}^{n} \mu_{li}(x_i(k))\right)^T}{\left\| \prod_{i=1}^{n} \mu_{li}(x_i(k)) \right\|^2} = \tag{17}$$

$$= W(k) + \left( d(k) - W(k)\left(\prod_{i=1}^{n} \mu_{li}(x_i(k))\right)\right)\left(\prod_{i=1}^{n} \mu_{li}(x_i(k))\right)^{+},$$

where $W(k) = \begin{pmatrix} w_{11}(k) & w_{12}(k) & ... & w_{h1}(k) \\ w_{21}(k) & w_{22}(k) & ... & w_{h2}(k) \\ \vdots & \vdots & \vdots & \vdots \\ w_{m1}(k) & w_{m2}(k) & ... & w_{mh}(k) \end{pmatrix}$ — $(m \times h)$- synaptic weights matrix; $d(k) = (d_1(k), d_2(k), ..., d_m(k))^T$ — reference signal, which contains information about the patients diagnosis and can take only two values of 0 or 1, $e(k) = (e_1(k), e_2(k), ..., e_m(k))^T$ — vector of training errors.

In situation when number of features of any patients or number of its possible diagnosis can be changed, HNFS architecture also changes (HNFS_evol — Fig. 8) [19].

If patient vector $x(k)$ is fed to the system input and it characterized by the same set of features as all previous patients and one more feature $n+1$:

$$x(k) = (x_1(k), ..., x_n(k), x_{n+1}(k))^T. \tag{18}$$

System evolution can be realized in the layer of membership function calculation, were new functions $\mu_{li}(x_i(k))$, $i = 1, 2, ..., n+1$, $l = 1, 2, ..., h$ appear. These functions are multiplied to $h$ values $\prod_{i=1}^{n+1} \mu_{li}(x_i(k))$ and HNFS_evolworks according to the equations(11)–(15).

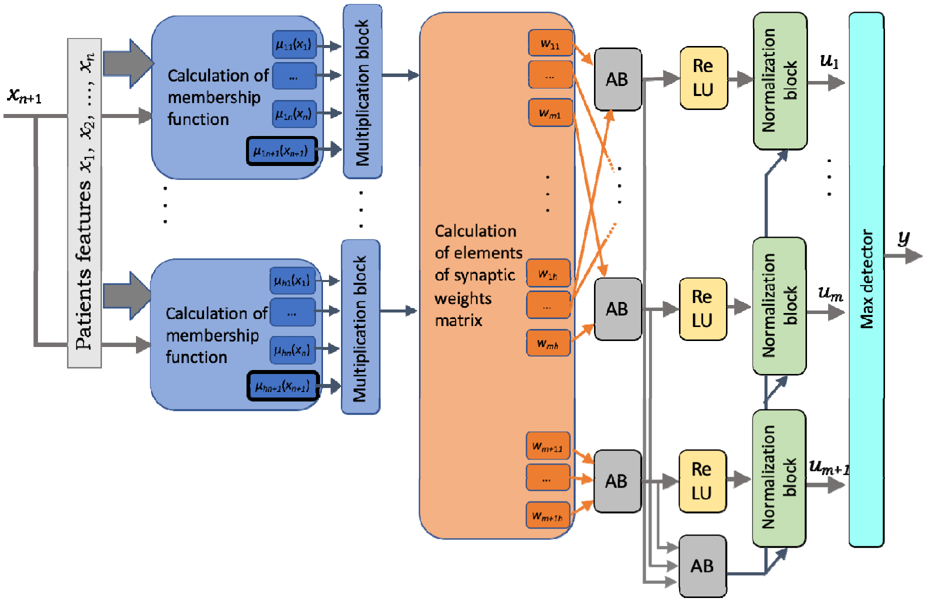


***Fig. 8.*** Hybrid neuro-fuzzy evolving system (HNFS_evol)

In situations when a patient is diagnosed with a new diagnosis, the HNFS_evol architecturally evolves at the level of synaptic weights calculation: a new synaptic weights $w_{m+11},\ldots,w_{m+1h}$, a ReLU activation function and one more normalization block for defuzzyfication system results appear in the system architecture. The most probable diagnosis is formed by the maximum detection block a:

$$y(k) = \max\{u_1,\ldots,u_m,u_{m+1}\}. \tag{19}$$

For training of HNFS_evol criterion (16) is used. For synaptic weights tuning we should concatenate the pre-trained matrix $W$ with a new weight-vector that corresponds to the new diagnosis:

$$W^*(k+1) = \begin{pmatrix} W(k+1) \\ ------ \\ w_{m+1}(k+1) \end{pmatrix} = \begin{pmatrix} W(k) \\ ---- \\ w_{m+1}(k) \end{pmatrix} + \\ + \frac{\left(\begin{pmatrix} d(k) \\ ---- \\ d_{m+1}(k) \end{pmatrix} - \begin{pmatrix} \tilde{x}(k) \\ ---- \\ \tilde{x}_{m+1}(k) \end{pmatrix}\right)\left(\prod_{i=1}^{n} \mu_{li}(x_i(k))\right)^T}{\left\|\prod_{i=1}^{n} \mu_{li}(x_i(k))\right\|^2}. \tag{20}$$

So synaptic weights matrixis transformed to the form of $\left((m+1)\times h\right)$-matrix:

$$W^{*}(k)=\begin{pmatrix} w_{11}(k) & w_{12}(k) & \dots & w_{1h}(k) \\ w_{21}(k) & w_{22}(k) & \dots & w_{2h}(k) \\ \vdots & \vdots & \vdots & \vdots \\ w_{m1}(k) & w_{m2}(k) & \dots & w_{mh}(k) \\ w_{(m+1)1}(k) & w_{(m+1)2}(k) & \dots & w_{(m+1)h}(k) \end{pmatrix}. \quad (21)$$

This matrix must be trained on $m+1$ diagnosis without retraining previously trained synaptic weights for $m$ diagnosis.

## UNSUPERVISED LEARNING MODE

The need of using unsupervised learning methods arises in mass health examination when the diagnosis of all patients is unknown or they are considered conditionally healthy. Structural diagram of a method of adaptive robust fuzzy clustering of a patient features using a Manhattan metricsis shown in Fig. 9 [23].

For calculating distances in Manhattan metrics between $x(k)$ and $c_m$ we can use:

$$dist\left(x(k),c_m\right)=\left|x(k)-c_m\right|. \quad (22)$$

Calculation of position of cluster centers $c_m$ and membership level of each patient to each of clusters $\mu_m$ is performed using self-learning algorithm [23]:

$$\begin{cases} \mu_m\left(x(k)\right)=\dfrac{\left\|x(k)-c_m(k)\right\|^{-1}}{\sum\limits_{l=1}^{m}\left\|x(k)-c_l(k)\right\|^{-1}}, \\ c_m(k+1)=c_m(k)+\eta(k)\mu_m^2\left(x(k)\right)sign\left(x(k)-c_m(k)\right). \end{cases} \quad (23)$$

Thus, the diagnostic physician receives the degree of membership of each patient to each of clusters-diagnosis.

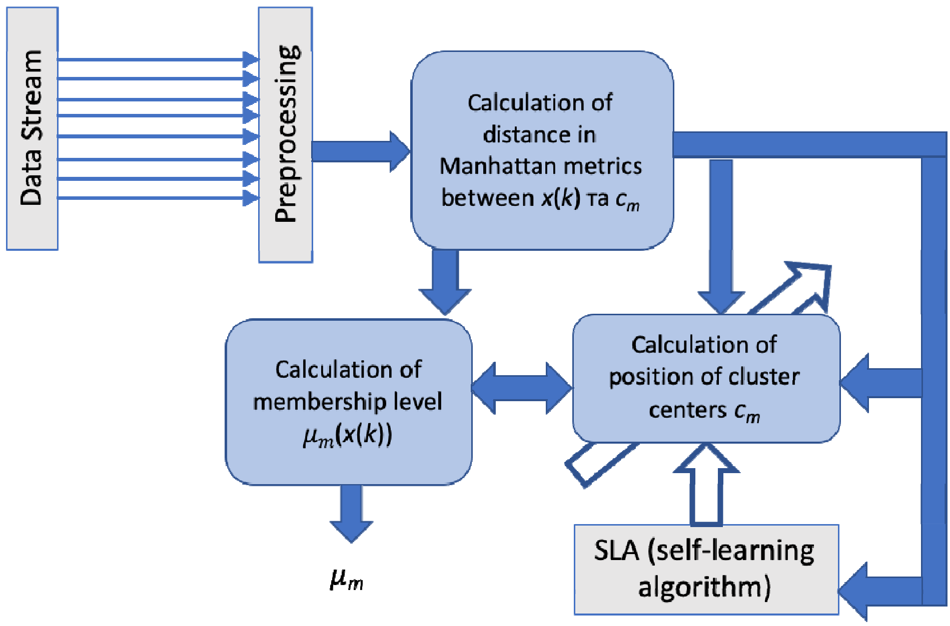


***Fig. 9.*** Method of adaptive robust fuzzy clustering of a patient features using a Manhattan metric

## ACTIVE LEARNING AND ASSOCIATIVE MODE

Approaches based on active learning are necessary in situations when a non-representative dataset is being processed, that is some patients diagnoses are known, but their numbers are insufficient for supervised learning mode [24–25].

In situations where the diagnosis of only a few patients are known, the use of associative neuro-fuzzy memory methods is appropriate. The associative clustering method based on neuro-fuzzy auto-associative memory realizes in few stages (Fig.10). At first stage a membership function is introduced, which can be described by (11) and its centers correspond to features of patients with known diagnosis with which it is necessary to associate. Width parameter of Gaussian functionis adjusted using level $\Delta$ that corresponds to a given level of intersection of two neighboring membership functions.These membership functions are fed to the multiplication blocks, in which values $\prod_{i=1}^{n}\mu_p(x_i)$ are calculated. These values are summarized $\sum_{p=1}^{m}\prod_{i=1}^{n}\mu_p(x_i)$ at adder block. A normalizing procedure is realized at the system output:

$$u_p(x)=\frac{\prod_{i=1}^{n}\mu_p(x_i)}{\sum_{p=1}^{m}\prod_{i=1}^{n}\mu_p(x_i)},\ p=1,2,\ldots,m. \quad (24)$$

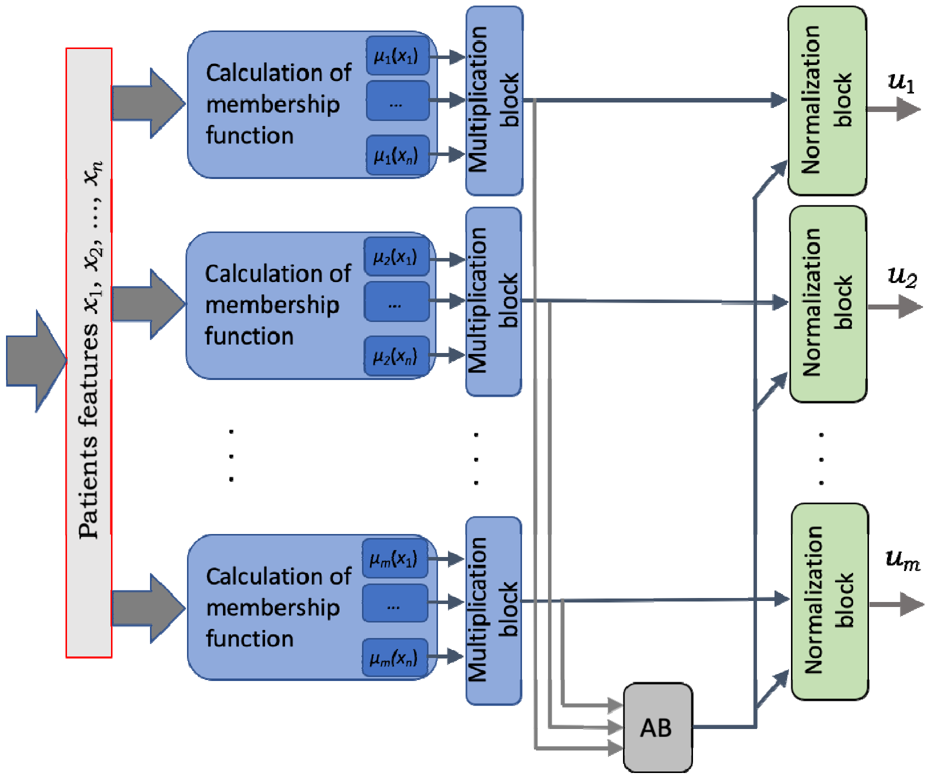


***Fig. 10.*** Associative neuro-fuzzy memory

Thus, when patient's feature-vector is fed to the system input, signals $u_p(x)$ appear at the system output which correspond to levels of association with patients with known diagnosis.

As a part of the active learning mode, the neuro-fuzzy network with active learning is proposed. The system switches between self-learning and supervised learning modes, depending on whether the patient has a known diagnosis or not. In situations where the diagnosis is unknown, the system switches to self-learning mode and the first stage is the competition process when for each centroid-diagnosis $cd_j$ the distances $dist$ are calculated:

$$dist^2\left(cd_j(k), x(k)\right) = \left\| x(k) - cd_j(k) \right\|^2 . \quad (25)$$

Then the next step is the processes of cooperation and synaptic adaptation, presented in the form:

$$\begin{cases} cd_p(k+1) = \dfrac{cd_p(k) + \eta(k) u_p^2(k)\left(x(k) - cd_p(k)\right)}{\left\| cd_p(k) + \eta(k) u_p^2(k)\left(x(k) - cd_p(k)\right) \right\|} \quad \forall\ p = 1,2,\ldots,m, \\ 0 \le u_p(k) = \left\| x(k) - cd_p(k) \right\|^{-2} \left( \sum\limits_{l=1}^{m} \left\| x(k) - cd_l(k) \right\|^{-2} \right)^{-1} \le 1, \\ \eta(k) = r^{-1}(k), \quad r(k) = \alpha r(k-1) + 1, \quad 0 \le \alpha \le 1. \end{cases} \qquad (26)$$

In situations where the patient's diagnosis is known, the system switches to supervised learning, in which two situations may occur. If the feature vector falls into one of the specified Voronoi cells, the procedure for pulling up this particular centroid $cd_p(k)$ to $x(k)$ is implemented:

$$\begin{cases} cd_p(k+1) = \dfrac{cd_p(k) + \eta(k)\left(x(k) - cd_p(k)\right)}{\left\| cd_p(k) + \eta(k)\left(x(k) - cd_p(k)\right) \right\|}, \ \forall\ p = 1,2,\ldots,q, \\ \eta(k) = r^{-1}(k), \quad r(k) = \alpha r(k-1) + 1, \quad 0 \le \alpha \le 1. \end{cases} \qquad (27)$$

In a situation when $x(k)$ falls in a Voronoi cell with a centroid winner $cd_j^*(k)$ that does not relate to particular diagnosis, the center of gravity is pushed away from $x(k)$:

$$\begin{cases} cd_j(k+1) = \dfrac{cd_j^*(k) - \eta(k) \dfrac{\left(1 - \cos\left(cd_j(k), x(k)\right)\right)^{-1}}{\sum\limits_{l=1}^{m} \left(1 - \cos\left(cd_l(k), x(k)\right)\right)^{-1}} \left(x(k) - cd_j^*(k)\right)}{\left\| cd_j^*(k) - \eta(k) \dfrac{\left(1 - \cos\left(cd_j(k), x(k)\right)\right)^{-1}}{\sum\limits_{l=1}^{m} \left(1 - \cos\left(cd_l(k), x(k)\right)\right)^{-1}} \left(x(k) - cd_j^*(k)\right) \right\|}, \\ \eta(k) = r^{-1}(k), \quad r(k) = \alpha r(k-1) + 1, \quad 0 \le \alpha \le 1. \end{cases} \qquad (28)$$

## PERFORMANCE CRITERION

To compare the effectiveness of online medical diagnosis methods, the quality information criterion (Performance Criterion *PerCr*) was provided, taking into account the *Fault* diagnosis and the time for decision making (*Time*) required to process one patient:

$$PerCr = \lambda_1 Fault + \lambda_2 Time \,, \quad (29)$$

where $\lambda_1, \lambda_2$ — weighting coefficients that are chosen under the conditions that $\sum \lambda = 1$.

By analyzing the processing time for diagnostics of one patient, it was assumed that the processing time (Time) should be normalized [0;1] where 0 corresponds to a zero processing time and 1 to a possible maximal processing time equal to 1 ms. For diagnostic tasks in the data stream mode a value of performance criterion should be from 0 to 0.25, acceptable from 0.25 to 1 under the conditions of controlling the accuracy of diagnostics. All the results were obtained using MacBook (Retina 12-inch, Early 2016), processor 1,1 GHz Intel Core m3, 8 Gb 1867 MHz LPDDR3. Python 3.7 programming language in Spyder 3.3.2 was used for programming.

## RESULTS OF RESEARCH IN SUPERVISED LEARNING MODE

Approbation of the developed approach in supervised learning mode for patients with urological diseases on the basis of evaluating the information content of the symptom complex was conducted. The medical sample contained information about features of patients with six urological diagnoses. The number of patients who participated in the study was 188, each described by 106 features. At first step Feature Selection-Extraction method was used to evaluate the informativeness of the features, number of features was reduced to 12. At second step all 188 patients were divided into training and testing sets (126 patients were in the training set, 62 patients were in the testing set). Table 1 lists the training and testing errors of multidimensional neo-fuzzy neuron and the value of the performance criterion.

It is easy to see that error percentage and performance criterion were less when input data were represented by 12 features compared to initial 106 features.

A fuzzy diagnostics of the pharmacoresistant form of epilepsy using a multidimensional neo-fuzzy neuron was performed. Examination of 309 patients with epilepsy was used as input data, the experience of the disease in each of the patients was at least one year. The total number of features was 25. All patients were divided into two groups: the first group with efficacy of drug treatment and the second group were patients with pharmacological resistance. A visualization of position of the classes-diagnosis in the space of the first three principal components is presented in Fig. 11.

*Table 1.* **Results for multidimensional neo-fuzzy neuron**

| | Errors | | *PerCr* |
|---|---|---|---|
| | Training set | Testing set | |
| All features (106) | 7.19 % | 11.11 % | 0,085 |
| The most informative features (12) | 5.3 % | 6.4 % | 0,0545 |

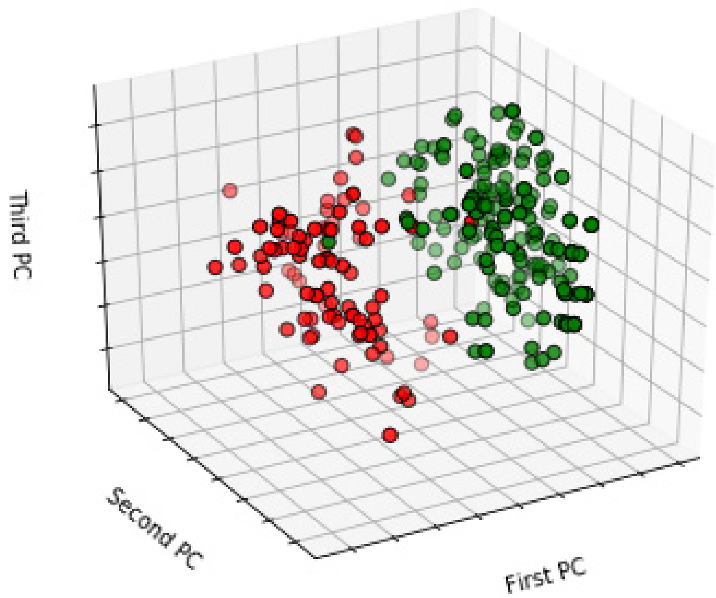


***Fig. 11.*** Dataset was divided into training and testing sets in a ratio of 206 patients to 103 patients. The results of multidimensional neo-fuzzy training and testing were presented in Table 2.

*Table 2.* **Results for multidimensional neo-fuzzy neuron**

| | Errors on training set (206 patients) | Errors on testing set (103 patients) |
|---|---|---|
| Number of patients | 2 | 6 |
| % of patients | 0,97 | 5,82 |
| *PerCr* | 0,0683 | 0,0501 |

Approbation of the hybrid neuro-fuzzy system (HNFS) and hybrid neuro-fuzzy evolving system (HNFS_evol) in supervised learning mode performed on datasets from UCI Repository [26-29]. In the first step, datasets were normalized at interval $x_i \in [0,1]$. The columns corresponding to the patient's health status (5$^{th}$ for the Iris.data, 9$^{th}$ for Pima-indian-diabetes.data, 35$^{th}$ for dermatology.data and 17$^{th}$ for parkinson.data) were moved to the vector $d(k)$. In the next step, one random attribute was removed from all datasets. The system was trained on $n$ features, after this deleted attribute was returned. The results are shown in Table 3.

All values of the performance criterion are acceptable for Medical Data Mining Tasks (its value is more than 0.25) in situations where the data is received sequentially, including situations when it is necessary to work in the conditions of data stream.

In the next phase of the approbation, patients with one of the diagnosis classes were excluded from all datasets. The system was trained on $n+1$ attributes and $m$ diagnoses. Further removed patients were added to the experiment. The classification results are shown in Table 4.

Thus, it should be noted that the HNFS, HNFS_evol and procedures of its training showed a high percentage of correct classification for medical diagnosis tasks. Testing the operation of a system on three medical datasets confirms its performance in overlapping diagnostic classes on small datasets with variable numbers of features and diagnoses.

*Table 3.* **Classification results for HNFS and HNFS_evol**

| Dataset | % errors for $n$ features / Time(*HNFS*) | | % errors for $(n+1)$ features / Time(*HNFS_evol*) | |
|---|---|---|---|---|
| | Training set | Testing set | Training set | Testing set |
| Iris.data | 1,4 % /130 µs | 2,68 % /70 µs | 3,57 % /128 µs | 8,23 % / 70 µs |
| Dermatology.data | 0,87 % /171 µs | 6,5 % /91 µs | 4,75 % /158 µs | 16,55 % /90 µs |
| Pima-indian-diabetes.data | 0,45 % /136 µs | 7,33 % /79 µs | 0,25 % /135 µs | 7,94 % /77 µs |
| Parkinson.data | 1,33 % /135 µs | 4,66 % /81 µs | 0,56 % /132 µs | 7,92 % /76 µs |
| *PerCr* | < 0,0898 | < 0,07615 | < 0,0102 | < 0,127 |

*Table 4.* **Classification results for HNFS and HNFS_evol**

| Dataset | % errors for $m$ diagnosis / Time (*HNFS*) | | % errors for $(m+1)$ diagnosis / Time (*HNFS_evol*) | |
|---|---|---|---|---|
| | Training set | Testing set | Training set | Testing set |
| Iris.data | 1 % / 820 µs | 2 % / 640 µs | 9 % / 850 µs | 16,6 % / 630 µs |
| Dermatology.data | 0,5 % / 980 µs | 4 % / 690 µs | 13,16 % / 990 µs | 20 % / 720 µs |
| *PerCr* | < 0,492 | < 0,365 | < 0,56 | < 0,46 |

## RESULTS OF RESEARCH IN THE ACTIVE TRAINING AND ASSOCIATION MODE

Approval of the developed approach in the mode of active training and association on the data of patients with pulmonary diseases was tested. The medical data set consists of 132 patients, each is characterized by 104 features (gender, age, patient complaints — 24 features, medical history — 14 features, objective description of the patient's condition — 26 features, clinical blood test — 10 features, biochemical blood test — 8 features, clinical analysis of urine — 10 features, chest radiography — 6 features, ECG — 8 features, spirometry — 2 features).

The entire data set was divided into three groups-diagnosis: 46 patients with chronic obstructive pulmonary disease, 53 patients with bronchial asthma, and 33 patients with pneumonia. Data visualization in the space of the three principal components is presented in Fig.12.

*Table 5.* **The results of fuzzy association patients**

| Patients ID | $\Delta$ -value | Errors | $PerCr$ -value |
|---|---|---|---|
| ID25 | 0.2 | 18,15 % | 0,469 |
| | 0.5 | 24,7 % | 0,502 |
| ID64 | 0.2 | 21,44 % | 0,486 |
| | 0.5 | 35,8 % | 0,558 |
| ID18 | 0.2 | 26,7 % | 0,512 |
| | 0.5 | 30,66 % | 0,532 |
| ID32 | 0.2 | 19,75 % | 0,477 |
| | 0.5 | 25,78 % | 0,507 |
| ID65 | 0.2 | 17,89 % | 0,468 |
| | 0.5 | 19,9 % | 0,478 |
| ID70 | 0.2 | 21,33 % | 0,485 |
| | 0.5 | 30,02 % | 0,529 |

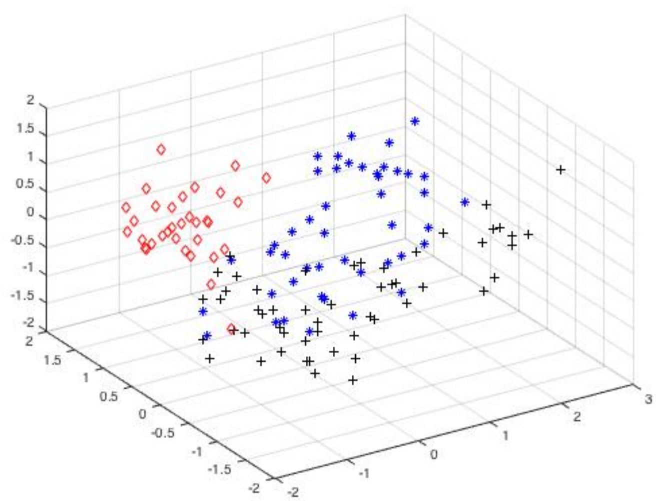

***Fig. 12.*** Data visualization: ◊ — patients with pneumonia; * — patients with chronic obstructive pulmonary disease; + — patients with bronchial asthma.

The physician identified the most typical representatives of each of the disease groups (five for each group). All other patients were fed to the system input unmarked (with unknown diagnosis). The neuro-fuzzy network with active learning showed the percentage of correctly classified patients at the level of 84.38 %. One patient's processing time is $Time = 36$ µs. Performance criterion value is $PerCr = 0.0961$.

Associative neuro-fuzzy memory methods were used for fuzzy diagnostics of hypertension and coronary heart disease.The following medical data of patients were obtained: age, gender, patient complaints coded from 0 to 1 (12 features), the value of clinical (8 features) and biochemical (22 features) analysis, heart rate. So, each of the patients can be represented as a vector containing 44 features. The total number of patients was 95. Physicians identified 6 patients who could be considered as the most representative of each group (patients with ID18, ID25, ID64 for hypertension; patients with ID32, ID65, ID70 for ischemic heart disease). The results of fuzzy association at different values of centers of fuzzy membership functions are shown in Table 5 with different parameters $\Delta$ . The best percentages of association with value of $\Delta = 0.2$ has shown for patient with ID65 and ID25, as evidenced by the minimum value of the performance criterion.

## CONCLUSION

Online medical data stream mining based on adaptive neuro-fuzzy approaches in the mode of supervised, unsupervised and active learning was considered.Special learning algorithm for neuro-fuzzy systems training was introduced. The proposed approaches allow obtaining additional information about patient diagnosis in conditions of limited a priori information about patient.Testing results on clinical medical data confirm the efficiency of the developed approaches.

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## ІНТЕЛЕКТУАЛЬНИЙ АНАЛІЗ ПОТОКІВ МЕДИЧНИХ ДАНИХ НА ОСНОВІ НЕЙРО-ФАЗЗІ ПІДХОДУ

**Вступ.** Підходи інтелектуального аналізу даних в завданнях медичного діагностування мають ряд особливих властивостей, які не дають змогу використовувати такі підходи в класичній формі. З цієї причини було розроблено адаптивні нейро-фаззі системи для завдань оброблення потоку медичних даних в режимі онлайн і алгоритми їхнього навчання. Запропоновані системи можуть обробляти потоки медичних даних в трьох режимах: у контрольованому навчанні, неконтрольованому навчанні та активному навчанні.

**Метою статті є** розроблення підходу, основаного на адаптивних нейро-фаззі системах, для розв'язання завдань оброблення потоків медичних даних в онлайн-режимі.

**Методи.** Для оброблення потоків медичних даних використовуються методи обчислювального інтелекту і, перш за все, штучні нейронні мережі, нейро-фаззі системи, нео-фаззі системи, їхнє контрольоване навчання, самонавчання і активне навчання, градієнтні методи оптимізації, методи еволюційних систем.

**Результати.** Проведено апробацію розробленого підходу в режимі контрольованого навчання за допомоги багатовимірного нео-фаззі нейрона з використанням медичних даних пацієнтів з урологічними захворюваннями. Відсоток помилок під час тестування системи з використанням всього простору ознак становить 11,11 %, з використанням найінформативніших ознак — 6,4 %. Також для діагностування фармакорезистентної форми епілепсії було використано багатовимірний нео-фаззі нейрон, відсоток помилки склав 5,82 %. Проведено апробацію розробленого підходу в режимі активного навчання та асоціації за даними пацієнтів із захворюваннями легень. Для всіх результатів апробації було розраховано критерій ефективності, його значення є задовільними для завдань медичного діагностування в режимі потоку даних.

**Висновки.** Запропонований підхід дає змогу отримати додаткову інформацію про діагноз пацієнта в умовах обмеженої апріорної інформації про пацієнта.

***Ключові слова:*** *адаптивна система, нейро-фаззі система, інтелектуальне оброблення медичних даних, потік медичних даних.*

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## ИНТЕЛЛЕКТУАЛЬНЫЙ АНАЛИЗ ПОТОКОВ МЕДИЦИНСКИХ ДАННЫХ НА ОСНОВЕ НЕЙРО-ФАЗЗИ ПОДХОДА

**Введение.** Подходы интеллектуального анализа данных в задачах медицинской диагностики обладают рядом особых свойств, которые не позволяют использовать их в классической форме. По этой причине были разработаны адаптивные нейро-фаззи системы для задач обработки потока медицинских данных в режиме онлайн и алгоритмы их обучения. Предлагаемые системы могут обрабатывать потоки медицинских данных в трех режимах: контролируемом обучении, неконтролируемом обучении и активном обучении.

**Цель статьи** — разработка подхода, основанного на адаптивных нейро-фаззи системах, для решения задач обработки потоков медицинских данных в онлайн-режиме.

**Методы.** Для обработки медицинских потоков данных используются методы вычислительного интеллекта и, прежде всего, искусственные нейронные сети, нейро-фаззи системы, нео-фаззи системы, их контролируемое, само- и активное обучение, градиентные методы оптимизации, методы эволюционирующих систем.

**Результаты.** Проведена апробация разработанного подхода в режиме контролируемого обучения с применением многомерного нео-фаззи нейрона при использовании медицинских данных пациентов с урологическими заболеваниями. Процент ошибок при тестировании системы с использованием всего пространства признаков составляет 11,11 %, с использованием наиболее информативных признаков — 6,4 %. Также для диагностики фармакорезистентной формы эпилепсии был использован многомерный нео-фаззи нейрон, процент ошибок составил 5,82 %. Проведена апробация разработанного подхода в режиме активного обучения и ассоциации по данным пациентов с заболеваниями легких. Для всех результатов апробации был рассчитан критерий эффективности, его значения являются удовлетворительными для задач медицинского диагностирования в режиме потока данных.

**Выводы.** Предложенный подход позволяет получить дополнительную информацию о диагнозе пациента в условиях ограниченной априорной информации о пациенте.

***Ключевые слова:*** *адаптивная система, нейро-фаззи система, интеллектуальный анализ медицинских данных, поток медицинских данных.*

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# CONSTRUCTION OF A COMPUTER TECHNOLOGY FOR INFORMATION SUPPORT OF DECISIONS IN THE FOUNDRY PRODUCTION PROCESS

***Introduction****. To ensure the high-quality manufacture of foundry products, advanced computer technologies are required which would contain not only a database of metals and alloys but also information on defect formation processes and methods for producing castings of a given quality. Software development requires detailed analysis not only of existing advanced technologies, but also the needs of the customer, compliance with all stages of the technological process, determination of the production profile.*

***The purpose of the paper*** *is to analyze existing approaches and tools used in the foundry support industry to develop a computer technology containing a database of Ukrainian standards and specifications and providing guidance on the tasks involved in the casting process. To construct such technology for supporting the foundry making in the casting process, it is necessary to identify the advantages and disadvantages of existing facilities, assess the feasibility of using these tools in the domestic production and formulate requirements for computer technology developed in accordance with specifics of the Ukrainian foundries and oriented to work with the domestic base of metals and alloys.*

***Results****. The analysis of modern software for computer modeling of processes in the field of formation of metals and alloys is carried out. It is planned to use the results of the analysis when creating a computer technology for modeling thermal processes in the field of foundry production focused on the Ukrainian industry to simplify the casting process. This will increase the production volume and reduce the appearance of defects in casting products during the technological process to make them more competitive. The block diagram of the computer technology of information support for decision-making in the foundry process is given. The main blocks of this system and the tasks they will solve are described.*

***Conclusions***. *An analysis of modern software for computer simulation of processes in the field of metal molding and the methods which are the basis of software products is executed. The results of the analysis are used when creating the computer technology of simulation of the thermal processes in the field of foundry, which will be oriented on Ukrainian industries, simplify the process of the casting obtaining. This will result in an increase of the production volume and reduce the appearance of defects in casting products during technological process to make them more competitive.*

***Keywords*: *casting, foundry production, computer technology, information support of decisions, group method of data handling (GMDH).*

## INTRODUCTION

Casting is a process in which various transformations are involved and it carries risk of failures producing defects in casting which ultimately leads to rejection of the casting product [1].

In order to provide fast and qualitative production of casting products, advanced computer technologies are needed that would contain not only the database of metals and their alloys, but also information on the processes of defect formation, methods of obtaining castings of the given quality for a particular production, conditions and factors that influence the structure of casting during thermal treatments.

The use of information technologies at the Ukrainian foundries means making adjustments to the structure of the production process and the correction of existing outdated software complexes, which currently use founders in the manufacture of metal products. Focusing on the best foreign information technologies, identifying their advantages and disadvantages, the principles and methods by which they operate, it becomes possible to create a qualitative technology for the founders, highlighting the main stages of working with the melt and its subsequent processing. The development of software requires a detailed analysis of not only existing advanced technologies, but also needs of the customer, the observance of all stages of the technological process, the definition of the profile of production, its specialization.

The aim of this work is to perform an overview of existing software tools for computer modelling of foundry processes, to determine their advantages and disadvantages, to evaluate the possibilities of using these tools at domestic production and to propose the way to constructing a computer technology developed in accordance with the requirements of Ukrainian foundry enterprises and oriented to work with the Ukrainian base of metals and alloys and suitable for implementation.

The importance of computer simulation is based on the accuracy of simulating the process' physics so that important process variables can be identified and controlled. Visualization of the pouring process in a virtual environment allows founders to timely see and eliminate problems associated with fluid flow, hardening and distortion of the part [2].

The casting process modeling will allow predicting the quality and accurate sizes of foundry products before production, which will significantly reduce the process of producing products and help to determine the possibility of defect formation to eliminate it as well as the chemical composition and mechanical properties of casting.

## OVERVIEW OF THE SOFTWARE USED IN THE FOUNDRY INDUSTRY

Today in the world various software products are used, which are related to metallurgical and foundry processes.

An overview of modern software in the field of molding has shown that today there are many different software products that are used by technologists-founders at the enterprises, but they are not available for a number of parameters for many industries, especially small ones, in particular, they are expensive, need constant updating and maintenance, but do not solve all the problems facing the foundry during the casting process [3, 4].

A comparative analysis of the most common computer systems for simulation of physical processes accompanying metallurgical and foundry technologies was done in [5]. Mathematical modeling of metallurgical and foundry processes, analysis of possible variants of their optimization related to the improvement of various technologies, allows reducing costs for preparation for production and manufacturing of castings.

Below we describe shortly the most used software in the world such as MAGMASOFT, ProCAST, LVMFlow / NovaFlow, POLYGON, advantages and disadvantages of these programs, their functionality.

Magmasoft simulates metal filling, crystallization, stress and strain calculation, structure, distribution of perlite and ferrite, and many other useful parameters.

In the base version, the MAGMASOFT standard allows you to simulate molding in sand-clay shapes and into chalk. For simulation of other types of casting it is necessary to purchase additional modules [6]:

• MAGMAlpdc (low pressure casting);

• MAGMAhpdc (high pressure die casting);

• MAGMAdisa (simulation of casting in the form of bezomaty forms for the DISAMATIC line);

• MAGMAiron (cast iron casting).

Flow Science, SantaFe, NewMexico, announced that they have released a new version of FLOW-3D Cast in software for the metal casting industry. FLOW-3D Cast v4.2 offers an advanced What You See Is What You Need (WYSIWYN) interface, process-oriented work space sand a new cooling model.

FLOW-3D Cast v4.2's WYSIWYN design methodology places the most important information at the top level so that users can quickly see and determine what options need to be set.

Following the design principle of WYSIWYN, FLOW-3D Cast v4.2 introduces the first process-oriented work space for high pressure die casting. Users are guided through the distinct stages of a high pressure die casting process – thermal die cycling, filling, solidification and cooling [7].

A large number of publications on various aspects of metal casting processes there appears to be a lack of gap in technology to specifically define process knowledge. Process knowledge is defined as the list of process variables, their collection system, visualization system and analysis to determine the ranges of relevant process variables that are related to the product characteristics for specific castings made in the foundries [8].

Conducted in [9] review shows that AFS Solid 2000 software combines thermal and volumetric calculations to predict shrinkage porosity. ProCAST uses finite element technique and has been adopted for micromodeling, stress, distortion, and automatic meshing. It is also applicable for sand, shell, die casting, permanent mold and lost foam processes. Foundries have used its software for improving the methoding and simulating the solidification process for producing radiographic quality castings. MeshCAST foundry software package is used for fully automatic 3-D mesh generation and is very convenient for design purposes. It can handle complex geometries, and generates the mesh at a faster rate. It is an automatic 3-D tetrahedral mesh generator. AutoCAST foundry software package is a knowledge-based system involving large eddy simulation for combining all the three essential tasks, casting design decisions, casting model creation and process simulation. This approach reduces the overhead of importing and exporting data between the systems for each layout iteration, saving time, and eliminates the possibility of making errors during data transfer.

The book [10] contains a broad collection of data on properties and characteristics for aluminum alloy castings, describes the factors that influence these properties, taking into account composition, microstructure, molding, heat treatment and quality assurance. Also presented are the curves of the heating and cooling process. These data are presented in agreed formats, which make it easy to compare different alloys and temperatures. The authors tried to consider all casting technologies that are available for aluminum alloys. The focus of the process is to review the influence of process selection and process variables on the properties and performance of casting.

In [11] a comparative analysis of the most common computer systems for modelling of physical processes accompanying metallurgical and foundry technologies was conducted. Mathematical modeling of metallurgical and foundry processes, analysis of possible variants of their optimization are connected with the improvement of various technologies which allow reducing costs for preparation for the production and manufacturing of castings. It is clear that at present it is impossible to unambiguously propose a computer system that would satisfy both factory technologists and engineer researchers. When choosing a computer system, the founder must take into account his financial capabilities, as well as the amount of tasks that need to be solved using a modern scientific tool.

In [12] advanced casting modelling tools like Procast™ allow the foundry engineer to quickly bridge the gap between design and manufacturing. Optimization or improved efficiency during the manufacturing cycle leads to substantial time and cost savings. Computer analysis provides the means for verifying design ideas and viewing the effects of “what ifs” at minimal costs by avoiding time-consuming and expensive rework and retooling.

## TECHNOLOGICAL PROCESSES OF GETTING CAST PRODUCTS

Metal casting is a technological process of obtaining various billets and parts. There are different casting methods which differ in their technology of obtaining castings.

The casting is an original design, which leads to the need to create an independent sprue-feeding system (SFS) for each casting, which serves to fill the mold with a metal by optimal speed, which excludes the formation of casting imperfections and nonmetallic inclusions, and compensation of volumetric shrinkage during the hardening of the casting to obtain in it a metal of a given density. SFS must meet the requirements of technological capability in the manufacture of models, molds and castings. However, molded parts have a lot in common in the sizes of walls, nodes, and their joints, thus opening up opportunities for typing SFS constructions and generating general methods for their calculations [12].

## EXISTING PROBLEMS AND FEASIBLE SOLUTIONS

The main direction of improvement of any production is the modernization of known and creation of new technological processes in order to reduce the consumption of materials, reduce energy and labor costs, improve working conditions, eliminate or reduce the harmful effects on the environment. All of this ultimately improves the efficiency of production and output [13].

The authors [11] concluded that it is currently impossible to unequivocally propose a computer system that would satisfy both factory engineers and engineer researchers. Consequently, when choosing a computer system, the founder must take into account the scope of tasks and production, the future use of products, which will result in the selection of the technological process of obtaining the workpiece or finished component, the type of metal or alloy and its financial capabilities. The survey showed that there is a need to develop a software product that would allow the following tasks to be performed:

1) calculation of the filling speed of the form;
2) calculation of hardening;
3) calculation of voltage;
4) thermal voltage;
5) the possibility of automatic computing;
6) analysis of defects;
7) analysis of the type of casting;
8) determination of cooling modes;
9) displaying the image of the process of pouring and freezing on the screen-visualization of the entire technological process, from the injection of molten metal to the form and before its solidification;
10) creating SFS for specific production;
11) analysis of casting of alloys.

In order to increase the competitiveness of graphitized steels with respect to such machine building materials as high-strength pig-iron, bronze, low-alloy steel, it is promising to create a new technology that provides the crystallization of hypereutectoid steel with the formation of spheroidal graphite inclusions and eliminating the formation of structural free cementite. This can be achieved by developing a highly effective modification application in the pre-crystallization period in combination with the optimization of the chemical composition and the rate of cooling of the castings.

As a result of the studies carried out in [14], a highly effective modification process was developed, the main technological parameters for obtaining hypereutectic alloy of steel with spheroidal graphite were determined. The obtained scientific results open the perspective of the development of highly effective technologies and creation of new brands of graphitized steel.

In foundries casting, defect analysis is one of the common applications of expert system. In modern foundries expert systems are mainly used for casting defect analysis. Expert systems are computer programs in which the knowledge and experience of one or more experts is captured and stored to make it widely available.

The knowledge in an expert system may originate from many sources such as textbooks, reports, databases, case studies, empirical data and personal experience. These systems can be of great assistance in the decision-making process as the computer can be made to think, reason, make inferences and give judgment, conclusions, and solutions to problems [9].

The emergence of software tools at the Ukrainian foundries not only simplifies the process of obtaining the casting, but also increases the volume and speed of production, will reduce the appearance of defects by improving the physical and chemical properties in the casting products.

Taking into account the direction of foundry factories, it becomes possible to create a software tool with auxiliary modules that will be oriented towards the type of casting and industry, the type of metal or alloy, the methods of obtaining casting, the analysis of the assessment of temperature impact on the material and characteristics of its physical properties.

## SAND CASTING TECHNOLOGY

The process of casting in sand forms is the process by which molten metal is poured into a sandy form. Sandblasting is a relatively cost-effective process with fast settings, ideally suited for prototyping or small production cycles. It can be used to produce components of almost any size and shape, from the simplest to the most complex. The precision of the sizes is good and the excellent surface texture can be achieved with the correct finish. Sand can also be recycled, providing both environmental and economic benefits.

Other characteristics of the form (volumetric, shell, refractory, etc.): composition and properties of molding mixtures, methods of their consolidation or hardening, characteristics of castings and alloys for their manufacture, scale of production, etc. determined only as variants of this process and types of equipment for performing specific operations [15].

The paper [16] considers the methods of casting, from which we have selected those that are oriented on the technology of casting in sand forms. Sand casting is the most common method of metal casting, accounting for approximately 75 percent of all metal cast. It consists of forming a cavity in sand with a pattern, filling the cavity with molten metal, allowing it to cool and solidify and then releasing the casting by breaking away the sand [17]. Shell-mold casting is a variation of sand casting in which sand containing a resin binder is cured by heat. Lost-foam casting is a technique similar to investment casting in that it uses an expendable pattern, one made of polystyrene foam rather than wax. The pattern is coated with a refractory material and then encased with sand, forming a one-piece sand mold.

## CONSTRUCTING A SPECIALIZED COMPUTER TECHNOLOGY IN FOUNDRY PRODUCTION

A computer support system for casting solutions is being developed. With its help, the specialist would have the opportunity to get recommendations on what impurities and in what proportions should be added to the initial raw materials and on the choice of a suitable cooling mode to achieve a certain quality of casting. Equally important is the displaying some images on the screen: visualization of the cooling curves of the casting (experimental data) and the content of raw materials by its chemical composition in the form of a diagram (mass fraction). The software is aimed at optimizing workflow support and casting process automation. General scheme of the main units and their relationships with the computer system is demonstrated (Fig. 1).

The system will consist of the three main blocks:

1. Database
2. Recommending subsystem (before production and in the process of manufacturing at a specific installation);
3. Analytical subsystem.

The recommending subsystem is linked to both the database and the analytical subsystem. The database contains standards, requirements, experimental data, and recommendations based on analytics on cooling process management.

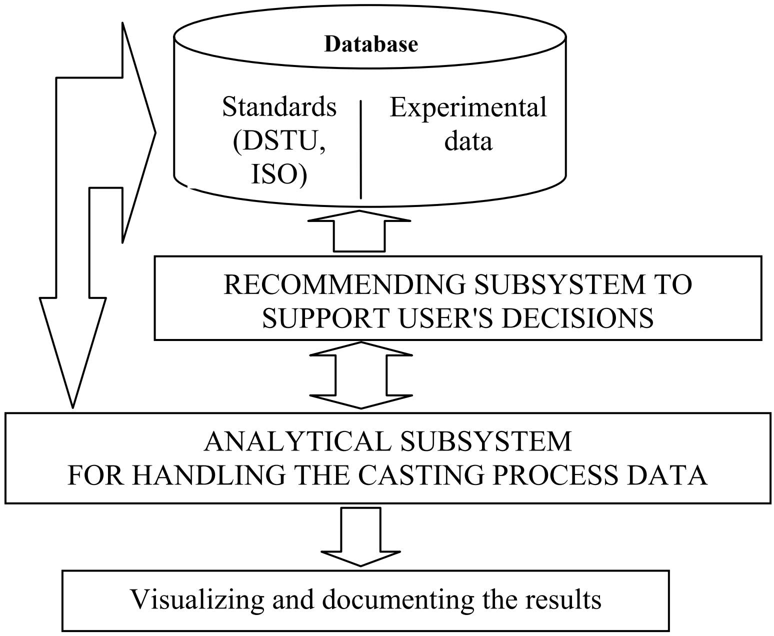


***Fig. 1.*** Flowchart of the foundry support system

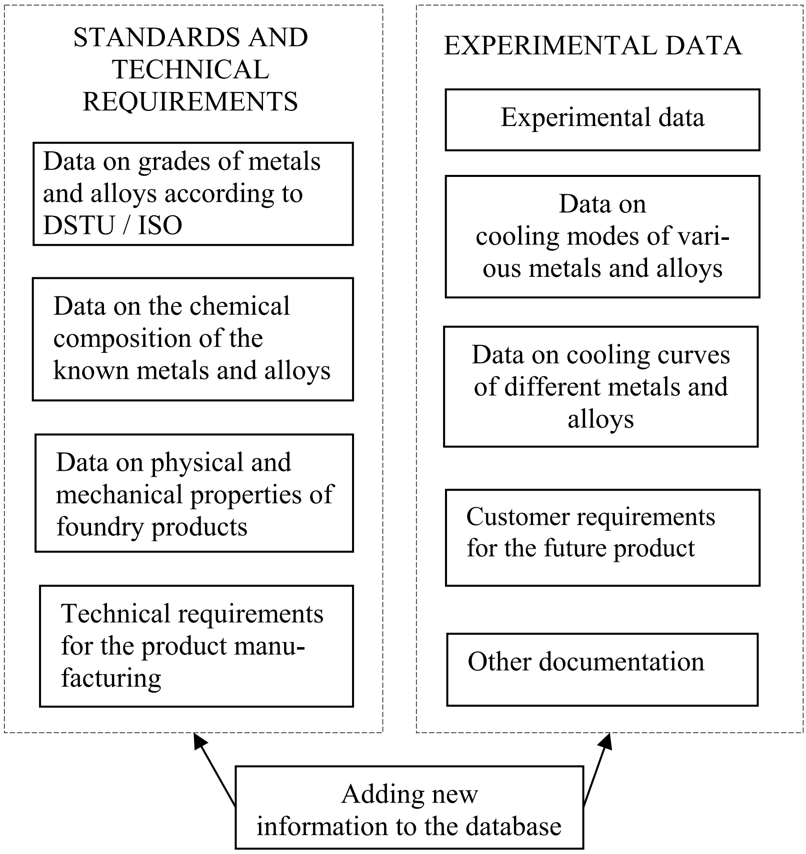


***Fig. 2.*** Block diagram of the database

The block diagram of the database is shown (Fig. 2).

The database consists of two main blocks. The first one contains standards and technical requirements. This data is independent of the installation on which the casting will be processed, it is invariant for all installations.

The second block contains the information of the casting user, which depends on the existing installations and conditions in which the process of casting and measuring the cooling temperature of the alloys takes place, as well as data on all the products that were manufactured and all other documentation required in the operating the casting machine at a specific installation. If necessary, this unit can be adapted for use on another installation with updating all the necessary information.

The user has the opportunity to supplement the database with new information both in the block of standards and specifications and in the block of data.

A flow chart of a recommending subsystem for supporting casting solutions which also consists of two separate blocks is presented (Fig. 3).

This subsystem can be used at the beginning of the casting (reference block) to determine what products can be made from the available raw materials if their chemical composition is known, to select from the database information about the selection of certain additional components of raw materials (its chemical composition) to obtain products of a given quality, and also to select from the experimental data of the user information about various alloys that were already made according to the technical requirements of the customer.

In the second block of the subsystem, for example, some types of recommendations are presented based on the results of the experiments performed and models constructed. This unit addresses the analytical subsystem and is intended to provide ongoing guidance to the caster during the casting process.

The analytical subsystem is intended for solving various computational tasks necessary for active support of the foundry maker's decisions. As for now, the following three tasks are implemented in this subsystem:

- construction of models of dependence of the intermediate temperature of casting on the mode of its cooling;
- construction of models of dependence of mechanical properties of a product on the chemical composition of raw materials;
- comparison of the curve of the unknown alloy curve with the standard curves of standard alloys introduced into the database.

The construction of models of temperature dependence on cooling modes makes it possible to use the simulation results to select a suitable cooling mode. This can be done by calculations of the intermediate temperature in different modes [18].

The construction of models of dependence of the mechanical properties of casting on the chemical composition of raw materials makes it possible to adjust the chemical composition of raw materials to obtain certain products. It also helps to evaluate how the increase or decrease of each of the components of the raw material affects the mechanical properties of the finished casting [19].

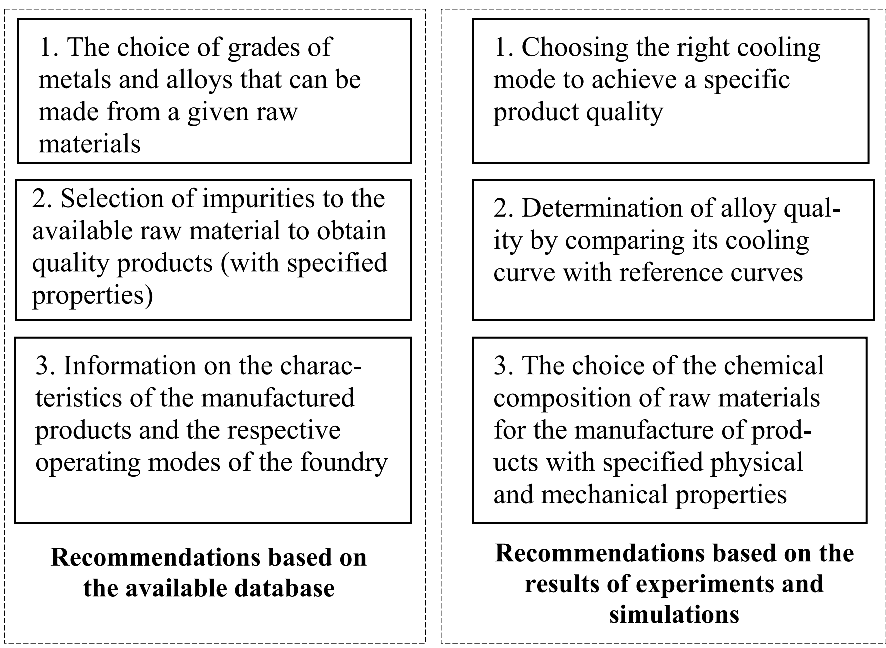


***Fig. 3.*** Flow chart of the recommending subsystem

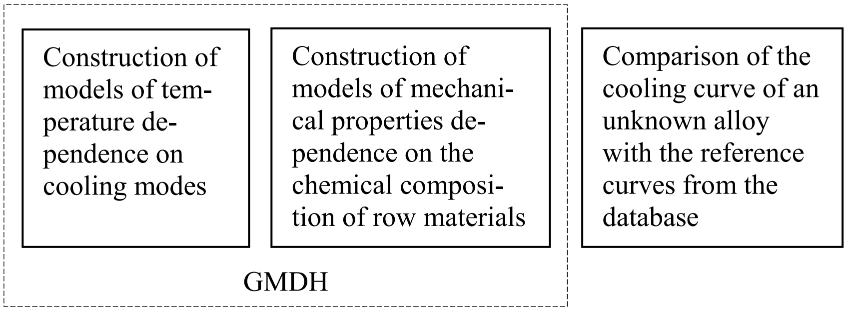


***Fig. 4*** Scheme of the analytical subsystem (an example)

The third problem which can be solved with the help of the analytical subsystem is to compare the proximity of a curve of an unknown alloy with the reference curves entered in the database, which allows determining its chemical composition.

The block diagram above presents a computer support system for the foundry and its main subsystems. Individual modules are developed using the VBA MS Excel language. This software package can be used on any Windows PC with MS Office installed. Given that the process monitoring data is in Excel or easily imported, such a product will be easy to use and will not require a special training.

The proposed technology substantially develops, supplements and clarifies the general principles of designing the computer technology for modeling the thermal processes of foundry production described in [20].

## CONCLUSIONS

On the basis of the overview of processes and methods of casting with the main attention to the detailed consideration of the methods of casting in the sandy form, we can draw the following conclusions.

The advantages of the molding method in sand forms are: the possibility of manufacturing castings of high weight and of complex forms; ability to automate production; castings are made from cast alloys, besides refractory that allows using scrap in remelting; cheap cost of receiving castings.

The disadvantages include the following: roughness of the surface which requires further treatment of castings and leads to a large amount of waste; the probability of defects occurrence is of greater extent than in other methods of casting; bad sanitary conditions of production.

Although sand casting technology has certain disadvantages, it still remains one of the most widely used casting technologies in the world due to the possibility of creating any shape of various sizes at a low price.

Therefore the creating computer technologies that will take into account all the peculiarities and help to enhance the casting quality is obviously of great importance. The paper presents the design features of a technology oriented to support casting solutions in the process of casting cooling. It is designed to automate some stages of the casting process as well as help specialists to make the casting process more manageable and replace costly experiments with their modeling to evaluate the influence of various factors on the casting during the cooling process.

The general scheme of technology for support of decisions of the foundry and its main subsystems – recommending and analytical, as well as the structural scheme of the database as a necessary component of the developed technology are presented.

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## КОНСТРУЮВАННЯ КОМП'ЮТЕРНОЇ ТЕХНОЛОГІЇ ІНФОРМАЦІЙНОЇ ПІДТРИМКИ РІШЕНЬ У ПРОЦЕСІ ЛИВАРНОГО ВИРОБНИЦТВА

**Вступ**. Для забезпечення якісного виготовлення ливарних виробів необхідні передові комп'ютерні технології, які містили б не лише базу даних металів та сплавів, а й інформацію про процеси утворення дефектів, способи отримання виливків заданої якості, умови та чинники, які впливають на структуру лиття під час термічного оброблення.

Використання інформаційних технологій на українських ливарних підприємствах означає внесення змін у структуру виробничого процесу та виправлення наявних застарілих програмних комплексів, які наразі використовують засновники у виробництві металевих виробів. Зосереджуючись на кращих зарубіжних інформаційних технологіях, виявляючи їхні переваги та недоліки, принципи та методи, якими вони керуються, стає можливим створити для замовників якісну технологію, виділивши основні етапи роботи з розплавом та подальшого його переоблення. Розроблення програмного забезпечення вимагає детального аналізу не тільки наявних передових технологій, а й потреб замовника, дотримання всіх етапів технологічного процесу, визначення профілю виробництва, його спеціалізації.

**Метою дослідження** є аналіз сучасних підходів та засобів, що використовуються в галузі підтримки рішень ливарника з метою розроблення такої комп'ютерної технології, яка буде містити базу даних українських стандартів та технічних вимог і надаватиме змогу отримувати рекомендації щодо завдань, які виникають у процесі лиття.

**Результати**. Проведено аналіз сучасного програмного забезпечення для комп'ютерного моделювання процесів в галузі формування металів і методів, що лежать в основі програмних продуктів. Результати аналізу використано у створенні комп'ютерної технології моделювання теплових процесів у галузі ливарного виробництва, орієнтовану на умови промисловості України, що надасть змогу спростити процес отримання литва, внаслідок чого можна буде збільшити обсяг виробництва та зменшити появу дефектів ливарних виробів у технологічному процесі, що підвищить їхню конкурентоспроможність. Наведено блок-схему комп'ютерної технології інформаційної підтримки прийняття рішень у процесі ливарного виробництва. Описано основні блоки цієї системи і завдання, які вони будуть виконувати.

***Ключові слова:*** *лиття, ливарне виробництво, виливок, комп'ютерна технологія, інформаційна підтримка керувальних рішень, метод групового урахування аргументів (МГУА).*

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## КОНСТРУИРОВАНИЕ КОМПЬЮТЕРНОЙ ТЕХНОЛОГИИ ИНФОРМАЦИОННОЙ ПОДДЕРЖКИ РЕШЕНИЙ В ПРОЦЕССЕ ЛИТЕЙНОГО ПРОИЗВОДСТВА

Проведен анализ современного программного обеспечения для компьютерного моделирования процессов в области формирования металлов и сплавов. Результаты анализа планируется использовать при создании компьютерной технологии моделирования тепловых процессов в области литейного производства, которая будет ориентирована на промышленные условия Украины и позволит упростить процесс получения литья, в результате чего увеличится объем производства, уменьшится появление дефектов изделий в технологическом процессе, чтобы сделать их более конкурентоспособными.
Приведена блок-схема компьютерной технологии информационной поддержки принятия решений в процессе литейного производства. Описаны основные блоки этой системы и задачи, которые они будут решать.

***Ключевые слова***: *литье, литейное производство, отливка, компьютерная технология, информационная поддержка управленческих решений, метод группового учета аргументов (МГУА)*

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## PRINCIPLE OF TIME STRETCHING IN GAME DYNAMIC PROBLEMS


***Introduction.*** *There exists a wide range of mechanical, economical and biological processes evolving in condition of conflict and uncertainty, which can be described by various kind dynamic systems, depending on the process nature. This paper deals with the dynamic games of pursuit, described by a system of general form, encompassing a wide range of the functional-differential systems. The deciding factor in study of dynamic games is availability of information on current state of the process. In real systems information, as a rule, arrives with delay in time. Also, there are a number of problems for which Pontryagin's condition, reflecting an advantage of the pursuer over the evader in control resources, does not hold. Establishment of close relation between its time-stretching modification and the effect of variable information delay offers much promise for solving the above mentioned problems.*

***The purpose of the paper is*** *to deduce, sufficient conditions for termination of the games, for which Pontryagin's condition does not hold, by the use of the effect of information delay, to specify these conditions for the case of integro-differential dynamics, and to illustrate the obtained result with the model example.*

***Methods.*** *For investigation of the dynamic game of pursuit we apply the scheme of Pontryagin's First Direct method providing bringing of the trajectory of conflict-controlled process to the cylindrical terminal set at a finite moment of time. In so doing, construction of the pursuer's control is accomplished on the basis of the Filippov-Castaing theorem on measurable choice that insures realization of the process of pursuit in the class of stroboscopic strategies by Hajek. To deduce solution of the conflict-controlled integro-differentional system in the Cauchy form, the method of successive approximation is used.*

***Results.*** *It is shown that the dynamic game of pursuit with separated control blocks of the players and variable delay of information is equivalent to certain perfect information game. Based on this fact, the principle of time stretching is developed to study the games with complete information for which classic Pontryagin's condition, lying at the heart of all direct methods of pursuit, does not hold. The time-stretching modification of this condition, proposed in the paper, makes it feasible to obtain sufficient conditions for bringing the game trajectory to the terminal set at a finite moment of time. In so doing, the control of pursuer, providing achievement of the game goal, is constructed. These conditions are specified for the integro-diffential game of pursuit. By way of illustration, an example of integro-differential game of pursuit is analyzed in detail. The time stretching function, providing fulfillment of the modified Pontryagin's condition is found. Simple relationships between* *dynamics parameters and control resources of the players are deduced that provide feasibility of capture of the evader by the pursuer, under arbitrary initial states of the players.*

***Conclusion.*** *Thus, in the paper an efficient tool is developed for analysis of conflict situation, for example, interception of a mobile target by controlled object in condition of conflict counteraction. The situation is analyzed, when the pursuing object lacks conventional advantage in control resources over the evading counterpart, that is, the classic Pontryagin's condition does not hold. Suggested approach makes it feasible to realize the process of pursuit with the help of appropriate Krasovskii' counter-controls.*

***Keywords:*** *dynamic game, time-variable information delay, Pontryagin's condition, Aumann's integral, principle of time stretching, Minkowski' difference, integro-differential game.*

## INTRODUCTION

In the theory of dynamic games a number of efficient methods are created to make decision in conditions of conflict and uncertainty. They originated in fundamental works of R. Isaacs [1], L.S. Pontryagin [2], N.N. Krasovskii [3], L. Berkovitz [4], A. Friedman [5], O. Hajek [6], B.N. Pshenitchny [7] and their disciples, which are based on various mathematical ideas respective to availability of information to opposing sides in the course of game [8–10]. There exists a wide range of mechanical, economical and biological processes which can be described by dynamic systems of various kind, in particular, by the ordinary differential, difference, difference-differential, integral, integral-differential, partial differential and fractional equations, as well as by impulse systems, depending on the process nature [11]. Any disturbance, counteraction or inaccuracy readily leads to game situation. The deciding factor in study of dynamic games is availability of information on current state of the process, its prehistory or various kind counter-parts discrimination, that results in the problems of pursuit-evasion by position or in the class of stroboscopic, quasi- or $\varepsilon$-strategies.

Sometimes, in real systems information arrives with delay in time. It is shown that the dynamic game of pursuit with variable information delay is equivalent to certain perfect-information game with the changed dynamics and terminal set. It was first proved for the linear differential games with constant delay of information, then for the case of variable information delay [12]. This effect of information delay opened up possibilities for application of classic methods to analyze the games with delay of information [12], [13].

At the heart of the First Direct method, developed for solving the linear differential pursuit games, lies Pontryagin's condition [2]. This condition reflects an advantage of the pursuer over the evader in control resources in terms of the game parameters. However, there are a number of problems for which this condition does not hold, e.g. the problems of soft meeting (simultaneous coincidence of geometric coordinates and velocities of objects), pursuit problems for oscillatory processes or different inertia systems etc [14], [15], [16].

Analysis of Pontryagin's condition performed by Nikolskij [14] greatly advanced its understanding and was a contributory factor to the modification of this condition [17], prescribing construction of the pursuer's control on the basis of evader's one in the past. Unfortunately, analysis of the model example contains slips.

Establishment of close relation of the modified condition with the passage from the original game with perfect information to an auxiliary one with delayed information [18], [19] gave impetus to the development of efficient approach (the principle of time stretching) to solving complicated games of pursuit, namely, those for which Pontryagin's condition does not hold [19], [20], [21].

This paper deals with the dynamic games of pursuit, described by a system of general form that encompasses a wide range of the functional-differential systems. The gist of this approach consists in artificial abandoning the availability of information on the current evader's control to the pursuer. In fact, the passage is made from the original game with complete information to the game with the same dynamics and the terminal set, yet with special kind information availability delay. This delay is a function of time, decreasing as the game trajectory approaches the terminal set and vanishing as it hits the target. The central idea of the time stretching principle consists in introduction of certain function, called the time stretching function, in which terms the time delay is expressed in explicit form. Then the obtained game with delayed information is analyzed on the basis of its equivalence to the perfect-information game with the changed dynamics, for which Pontryagin's condition includes the time stretching function.

The time stretching principle proved its efficiency in solving the problems of soft meeting in various cases of second-order dynamics, for which formula for the time stretching function is deduced in explicit form, in their number, in the case of different-kind dynamics of the pursuer and the evader [20–22]. Simple conditions on the games parameters insuring feasibility of the pursuit termination are deduced. The geometric-descriptive situation of finding 'tracks' of the evader is studied in detail, that provides realization of the time stretching principle by the way of the pursuer following the evader's trajectory with delay in time [20].

In the paper the time stretching principle is applied to the dynamic games, described by a system of general form, encompassing a wide scope of the functional-differential systems. The result of investigation is specified for the integral-differential games of pursuit. To this end, we derive solution to the integro-differential system in the Cauchy form. In so doing, the method of successive approximations is used to solve the Volterra integro-differential equation of second order. To support the suggested technique, an example of integro-differential pursuit game is examined in detail.

## EFFECT OF INFORMATION DELAY IN THE DYNAMIC GAMES OF PURSUIT

Statement of the pursuit game usually includes a system of equations, describing the conflict-controlled process. But subsequent analysis of the game, as a rule, employs only presentation of the system solution. In the case of differential game it is the Cauchy formula. To begin with, we recall the impact of information delay in the dynamic games of pursuit, that is, the equivalence of the game with variable information delay to certain complete-information game with the changed object's dynamics and the terminal set and, on its basis, outline the time stretching principle.

Let a trajectory of the conflict-controlled process be given in the form:

$$z(t)=g(t)-\int_{t_0}^{t}\left(f_1(t,\theta,u(\theta))-f_2(t,\theta,v(\theta))\right)d\theta\,,\ t\in[t_0,+\infty). \tag{1}$$

Here $z(t)\in R^n$, where $R^n$ is the real $n-$dimensional Euclidean space, $g:[t_0,+\infty)\to R^n$ is continuous vector-function. Controls $u$ and $v$ are picked by the players at each instant of time from the compacts $U$ and $V$ in a way their realizations in time be Lebesgue measurable functions. Functions $f_1(t,\theta,u)$ and $f_2(t,\theta,v)$, $f_1 : \Delta(t_0)\times U \to R^n$, $f_2 : \Delta(t_0)\times V \to R^n$, where $\Delta(t_0) = \{(t,\theta): 0 \le t_0 < \theta \le t \le +\infty\}$ are assumed to be Lebesgue measurable both in $t$ and $\theta$ and continuous in $u$ and $v$, respectively; $U \in K(R^n)$, $V \in K(R^n)$, where by $K(R^n)$ is denoted the set of all non-empty compacts from $R^n$.

Besides, a terminal set $M_*$ having a cylindrical form is given:

$$M_* = M_0 + M . \qquad (2)$$

Here $M_0$ is a linear subspace of $R^n$ and $M$ — a convex compact from the orthogonal complement to $M_0$ in $R^n$, i.e. $M \in coK(L)$. By $coK(L)$ is meant the set of all convex sets from $K(R^n)$.

Let us denote by $\Omega_U$ and $\Omega_V$ the sets of all measurable functions taking their values in the compacts $U$ and $V$, respectively. In the sequel, they are referred to as the sets of admissible controls of the pursuer and the evader, respectively.

We analyze the game, standing on the pursuer side ($u$). The goal of the pursuer is at a finite moment of time to bring a trajectory of the system (1) to the terminal set $M_*$, under arbitrary admissible control of the evader ($v$). By the moment of the game termination is meant the first moment of time $t$ when $z(t) \in M_*$. Such dynamic game is called the game of pursuit.

Let $\pi$ be the operator of orthogonal projection from $R^n$ onto $L$, $\pi : R^n \to L$. Then bringing the system trajectory to the terminal set is equivalent to the inclusion $\pi z(t) \in M$. It is supposed that $g(t_0) \notin M_*$ and the players know the parameters of conflict-controlled process (1), (2), namely vector- functions $g(t)$, functions $f_1(t,\theta,u)$ and $f_2(t,\theta,v)$, the control domains $U$, $V$, and the terminal set $M^*$.

Let us suppose that current information on the game state become available to the pursuer with the delay in time $\tau(t)$. The function $\tau : [t_0 + \tau_0, +\infty) \to R$, $\tau(t_0 + \tau_0) = \tau_0$ is assumed to be piecewise-continuous, besides, it can have at most countable number of discontinuities and all discontinuities are of the first order, and is absolutely continuous on the intervals of its continuity. What is more, $\dot{\tau}(t) < 1$ at the points at which the derivative $\dot{\tau}(t)$ exists. The last condition provides for access of fresh information in the course of the game.

The game starts at the moment $t_0$ but information on the evader control becomes available to the pursuer only beginning from the moment $t_0 + \tau_0$, $\tau_0 > 0$. In the course of the game, i.e. at each current instant of time $t$, $t \ge t_0 + \tau_0$, the pursuer has access to information on the evader control at the moment $t - \tau(t)$. Denote by $u^t(\cdot)$ realization of the pursuer control on the half-interval $[t - \tau(t), t)$,

$$u^t(s)=\{u(s): s\in[t-\tau(t),t)\}.$$

We name the pair $(g(t),u^t(\cdot))$ by the position of game at the moment $t$. Suppose that on the initial half-interval $[t_0,t_0+\tau_0)$ the pursuer applies some admissible control $u^{t_0+\tau_0}(\cdot)$,

$$u^{t_0+\tau_0}(\cdot)=\{u(s): s\in[t_0,t_0+\tau_0)\},\ u^{t_0+\tau_0}(\cdot)\in\Omega_U.$$

The pair $(g(t_0),u^{t_0+\tau_0}(\cdot))$ is referred to as the initial position of the delayed-information game.

**Definition1.** Let $X$ and $Y$ be non-empty sets from $R^n$. The geometric difference of sets is defined by the formula

$$X \overset{*}{-} Y=\{z: z+Y\subset X\}=\bigcap_{y\in Y}(X-y).$$

In what follows, the notion of Aumann integral of set-valued mapping is used [23].

**Definition 2.** Let $F(t)$ be a measurable mapping, $F:[t_0,T]\to P(R^n)$, where $P(R^n)$ is a set of all closed subsets of the space $R^n$. The union of integrals, taken over all its measurable selections $f(t)$, $f(t)\in F(t)$, namely,

$$\bigcup_{f(\cdot)\in F(\cdot)}\int_{t_0}^{T} f(t)dt$$

is called the Aumann integral of set-valued mapping $F(t)$ and usually denoted by $\int_{t_0}^{T}F(t)dt$.

Let us take into consideration the following set-valued mappings

$$V(\tau(t))=\left\{x: x=\int_0^{\tau(t)} f_2(t,t-\theta,v(\theta))d\theta,\ v(\cdot)\in\Omega_V\right\},$$

$$M(\tau(t))=M\overset{*}{-}V(\tau(t))..$$

**Condition1.** The set-valued mapping $M(\tau(t))$ has non-empty images for all $t\ge t_0+\tau_0$.

Let us take a look at the pursuit game with complete information, starting at the moment $t_0+\tau_0$, which current state is defined by the formula

$$\tilde{z}(t)=\tilde{g}(t)-\int_{t_0+\tau_0}^{t} f_1(t,\theta,u(\theta))d\theta+\int_{t_0+\tau_0}^{t}(1-\dot{\tau}(\theta))f_2(t,\theta-\tau(\theta),v(\theta-\tau(\theta)))d\theta, \quad (3)$$

$$\tilde{z}(t_0+\tau_0)=\tilde{g}(t_0+\tau_0),\quad \tilde{g}(t)=g(t)-\int_{t_0}^{t_0+\tau_0} f_1(t,\theta,u(\theta))d\theta$$

and the terminal set $M_*(t)$ having the form of set-valued mapping,

$$M_*(t)=M_0+M(\tau(t)). \tag{4}$$

We observe that, by virtue of Condition 1, the terminal set $M_*(t)$ has the solid set component $M(\tau(t))$.

**Theorem1.** Let in the dynamic game (1), (2) with variable information delay $\tau(t)$ Condition 1 hold. Then this game can be terminated at the moment $T$, $T \ge t_0+\tau_0$, starting from the initial position $\left(g(t_0), u^{t_0+\tau_0}(\cdot)\right)$, if and only if the game (3), (4) with complete information can be terminated at the same time $T$.

## PRINCIPLE OF TIME STRETCHING IN DYNAMIC GAMES OF PURSUIT

Now we outline an approach to solving games of pursuit in the frames of the First Direct method [2] and derive sufficient conditions insuring the game termination at some finite time, which, generally speaking, is not optimal. In such case they say about guaranteed result. It is achieved by using counter-controls by Krasovskii [3], provided by stroboscopic strategies by O. Hajek [6]. We name this approach by the time stretching principle.

The First Direct method, created to study the linear differential games of pursuit is based on the Pontryagin's condition that reflects an advantage of the pursuer over the evader expressed in terms of the game parameters.

The linear differential game is described by the system of linear differential equations

$$\dot{z}(t)=Az(t)-u(t)+v(t),$$

$z \in R^n$, $z(0)=z_0$, $A$ is a quadratic matrix of order $n$. It presents a particular case of the conflict-controlled process (1) with

$$g(t)=e^{tA}z_0,\ f_1(t,\theta,u)=e^{(t-\theta)A}u,\ f_2(t,\theta,v)=e^{(t-\theta)A}v$$

(by $e^{tA}$ is denoted exponent of the matrix $tA$).

**Condition 2 (Pontryagin's condition).** The set-valued mapping

$$W(t)=\pi e^{tA}U \underline{*} \pi e^{tA}V \tag{5}$$

has non-empty images for all $t \in [0,+\infty)$.

Note, that in the case of linear differential game the state variable $\tilde{z}(t)$ of the equivalent game with complete information, evolving on the half-axis $[\tau_0,+\infty)$, satisfies the differential equation

$$\dot{\tilde{z}}(t)=A\tilde{z}(t)-u(t)+(1-\dot{\tau}(t))e^{\tau(t)A}v(t-\tau(t)),$$

$$\tilde{z}(\tau_0) = e^{\tau_0 A} z_0 - \int_0^{\tau_0} e^{(\tau_0 - \theta)A} u(\theta) d\theta$$

and the terminal set of the equivalent game appears as the set $M_*(t)$ (4) with

$$V(\tau(t)) = \left\{ x : x = \int_0^{\tau(t)} e^{\theta A} v(\theta) d\theta,\ v(\cdot) \in \Omega_V \right\}.$$

The set-valued mapping $W(t)$ (5) is applied in the First Direct Method as follows. It is shown that if at some time $t_1$ the initial state of the game $z_0$ satisfies the inclusion

$$\pi e^{t_1 A} z_0 \in \int_0^{t_1} W(\theta) d\theta,$$

then the game of pursuit can be terminated at the moment $t_1$ under arbitrary admissible controls of the evader.

Below we give generalization of Pontryagin's condition to the case of dynamics of general form (1).

**Condition 3.** $W(t,\theta) = \pi f_1(t_0 + t, \theta, U) \overset{*}{-} \pi f_2(t_0 + t, \theta, V) \neq \varnothing$, $t_0 \le \theta \le t < +\infty$.

In the case Condition 3 does not hold we propose its modification constructed with the help of the function of time stretching.

**Definition 3.** By the function of time stretching is named a non-negative, monotonically increasing function of time $I(t)$, $t \in [0, +\infty)$, $I(0) = 0$, $I(t) > t$, $t > 0$, which can have at most countable number of discontinuities and all discontinuities are of the first order, absolutely continuous on the intervals of its continuity, and such that $\sup_{t \in [0,+\infty) \setminus \Delta} \dot{I}(t) < +\infty$, where $\Delta$ is the set of $I(t)$ discontinuity and non-differentiability points.

**Condition 4.** There exists time-stretching function $I(t)$, such that the set-valued mapping

$$W_1(t,\theta) = \pi f_1(t, t_0 + I(t) - \theta, U) \overset{*}{-} \dot{I}(\theta) \pi f_2(t, t_0 + I(t) - I(\theta), V) \neq \varnothing,\ t_0 \le \theta \le t < +\infty.$$

**Theorem 2.** Let in the perfect-information game (1), (2) Condition 4 hold and let for the given initial state $g(t_0)$ there exist a finite moment of time $t_1$:

$$t_1 = \left\{ \min t : t \ge 0, \pi \left( g(t_0 + I(t)) - \int_{t_0}^{t_0 + I(t) - t} f_1(t_0 + I(t), \theta, U) d\theta \right) \right.$$
$$\left. \cap \left( M + \int_0^t W_1(t,\theta) d\theta \right) \neq \varnothing \right\}. \qquad (6)$$

Then a trajectory of the process (1) can be brought by the pursuer to the terminal set $M_*$ (2) at the moment of time $t_0 + I(t_1)$, under any admissible controls of the evader.

**Proof.** Let us set $\tau_0 = I(t_1) - t_1$ and divide the interval of time $[t_0, t_0 + I(t_1)]$ into two parts – the initial half-interval $[t_0, t_0 + \tau_0)$ and the closed interval $[t_0 + \tau_0, t_0 + I(t_1)]$. In view of the assumptions concerning non-emptiness of the intersection in definition of time $t_1$ (6) and non-emptiness of the images of the set-valued mapping $W_1(t, \theta)$ (Condition 4) there exist an admissible control $u^{t_0+\tau_0}(\theta)$, $\theta \in [t_0, t_0 + \tau_0)$, point $m$, $m \in M$, and measurable selection $w_1(t_1, \theta)$, $w_1(t_1, \theta) \in W_1(t_1, \theta)$, $\theta \in [0, t_1)$, such that the following equation is fulfilled:

$$\pi\left( g(t_0 + I(t_1)) - \int_{t_0}^{t_0+I(t_1)-t_1} f_1\left(t_0 + I(t_1), \theta, u^{t_0+\tau_0}(\theta)\right) d\theta \right) = m + \int_0^{t_1} w_1(t_1, \theta) d\theta . \quad (7)$$

We set the pursuer control on the initial time-interval $[t_0, t_0 + \tau_0)$ to be equal to $u^{t_0+\tau_0}(\cdot)$.

The trajectory of the conflict-controlled process (1) on the interval $[t_0 + \tau_0, t_0 + I(t_1)]$ can be presented in the form:

$$z(t_0 + \tau_0 + t) = g(t_0 + \tau_0 + t) -$$

$$-\int_0^t \left( f_1(t_0 + \tau_0 + t, t_0 + \tau_0 + \theta, u(t_0 + \tau_0 + \theta)) - f_2(t_0 + \tau_0 + t, t_0 + \tau_0 + \theta, v(t_0 + \tau_0 + \theta)) \right) d\theta .$$

Let us build current control of the pursuer at each instant of time $t_0 + \tau_0 + \theta$, $\theta \in [0, t_1]$ on the basis of the evader control at the instant $t_0 + I(t_1) - I(t_1 - \theta)$. It is easy to see that

$$t_0 + I(t_1) - I(t_1 - \theta) = t_0 + \tau_0 + \theta - \left( I(t_1 - \theta) - (t_1 - \theta) \right).$$

One can observe that in such case control of the pursuer at current instant $t_0 + \tau_0 + \theta, \theta \in [0, t_1]$, is constructed in accordance with the evader control at the moment on the time $I(t_1 - \theta) - (t_1 - \theta)$ earlier.

Thus, on the interval $[t_0 + \tau_0, t_0 + I(t_1)]$ transition is made from the original perfect-information game to the auxiliary game with the same dynamics and the same terminal set but with variable delay of information

$$\tau(t_0 + \tau_0 + \theta) = I(t_1 - \theta) - (t_1 - \theta), \ \theta \in [0, t_1]. \quad (8)$$

By Theorem1, this game with information delay is equivalent to the perfect-information game having the dynamics

$$\tilde{z}(t_0+\tau_0+t)=\tilde{g}(t_0+\tau_0+t)-\int_0^t f_1(t_0+\tau_0+t,t_0+\tau_0+\theta,u(t_0+\tau_0+\theta))d\theta+$$
$$+\int_0^t \dot{I}(t_1-\theta)f_2(t_0+I(t),t_0+I(t_1)-I(t_1-\theta),v(t_0+I(t_1)-I(t_1-\theta)))d\theta\,, \tag{9}$$

$$\tilde{g}(t_0+\tau_0+t)=g(t_0+\tau_0+t)-\int_{t_0}^{t_0+\tau_0} f_1\left(t_0+\tau_0+t,\theta,u^{t_0+\tau_0}(\theta)\right)d\theta\,.$$

The terminal set of the equivalent game has the form (4) with

$$M_*(t_0+\tau_0+t)=M_0+M(\tau(t_0+\tau_0+t)),$$
$$M(\tau(t_0+\tau_0+t))=M\underline{*}V(\tau(t_0+\tau_0+t))=M\underline{*}V(I(t_1-t)-(t_1-t))\,.$$

In view of the formula for the time delay (8), $\tau(t_0+I(t_1))=\tau(t_0+\tau_0+t_1)=0$, therefore, $M_*(t_0+I(t_1))=M_*$. Thus, at the moment of the game termination $t_0+I(t_1)$ the terminal set of the equivalent game is the set $M_*$.

Let us prescribe control of the pursuer on the interval $[t_0+\tau_0,t_0+I(t_1)]$ to be equal a measurable solution of the equation:

$$\pi f_1(t_0+I(t_1),t_0+\tau_0+\theta,u(t_0+\tau_0+\theta))=$$
$$=\dot{I}(t_1-\theta)\pi f_2(t_0+I(t_1),t_0+I(t_1)-I(t_1-\theta),v(t_0+I(t_1)-I(t_1-\theta)))+w(t_1,t_1-\theta)$$
$$\theta\in[0,t_1].$$

Such solution exists by virtue of the Filippov-Castaing theorem on a measurable choice [24].

With the help of the above formula, from the relationship (9) one can easily deduce that $\pi\tilde{z}(t_0+I(t_1))=m$, where $m\in M$. Therefore, at the moment $t_0+I(t_1)$ the trajectory of the original game (1) with complete information hits the terminal set $M_*$, under arbitrary control of the evader. In so doing, the pursuer constructs its current control on the basis of the evader's control in the past. The theorem is proved.

In case of the linear differential game Condition4 and Theorem2 take the forms of Condition5 and Theorem3, respectively.

**Condition 5.** [17]. There exists time-stretching function $I(t)$, such that the set-valued mapping

$$W_1(t)=\pi e^{tA}U\underline{*}\dot{I}(t)\pi e^{I(t)A}V$$

has non-empty images for all $t$, $0\le t<+\infty$.

**Theorem 3.** Let the linear differential game (5), (2) meet Condition 5 and suppose that for the given initial state $z_0$ there exists a finite instant of time $t_1$,

$$t_1 = t_1(z_0) = \min\left\{ t \geq 0 : \pi\left( e^{I(t)A} z_0 - \int_0^{I(t)-t} e^{(I(t)-\theta)A} U d\theta \right) \cap \left( M + \int_0^t W_1(\theta) d\theta \right) \neq \varnothing \right\}. \quad (10)$$

Then the game can be terminated by the pursuer at the time instant $I(t_1)$, under arbitrary admissible controls of the evader.

To this end, on the half-interval $[0, \tau_0)$ control of the pursuer is set equal to $u^{\tau_0}(\theta)$ and on the interval $[\tau_0, \tau_0 + t_1]$ it is built in the form of a measurable solution of the equation

$$\pi e^{(t_1-\theta)A} u(\tau_0 + \theta) =$$

$$= \dot{I}(t_1 - \theta)\pi e^{I(t_1-\theta)A} v(I(t_1) - I(t_1 - \theta)) + w_1(t_1 - \theta),\ \theta \in [0, t_1].$$

Note that control $u^{\tau_0}(\theta), \theta \in [0, \tau_0)$, where $\tau_0 = I(t_1) - t_1$ and measurable selection $w_1(\theta)$, $w_1(\theta) \in W_1(\theta)$, $\theta \in [0, t_1]$ are determined by the formula (10).

## INTEGRO-DIFFERENTIAL GAME OF PURSUIT

Let us consider two controlled systems evolving in $R^n$ according to the integro-differential equations, respectively:

$$\dot{x}(t) = A_1 x(t) + \lambda \int_0^t K(t,s) x(s) ds + f_1(u), u \in U, x(0) = x_0, \quad (11)$$

$$\dot{y}(t) = A_2 y(t) + \mu \int_0^t L(t,s) y(s) ds + f_2(v), v \in V, y(0) = y_0. \quad (12)$$

Here $A_1$ and $A_2$ are constant matrices, $K(t,s)$ and $L(t,s)$ are matrix functions whose elements are continuous on the set $\Delta = \{(t,s) : 0 \leq s < t < +\infty\}$; $f_1(u) : U \to R^n$ and $f_2(v) : V \to R^n$ are continuous vector- functions; $u$ and $v$ — control parameters of the pursuer and the evader, respectively; $\lambda$ and $\mu$ are real numbers.

The goal of the pursuer is in the shortest time to achieve meeting with the evader, i.e. $x(t) = y(t)$, $t < +\infty$ and the evader tries to escape or maximally postpone the meeting.

We assume that the pursuer constructs its control on the basis of information about initial states of the players and current control of the evader, i.e. employs counter-controls by N.N. Krasovskii [3].

Solutions to the equations (11), (12), under the initial state $x(0) = x_0$, $y(0) = y_0$ and chosen controls $u(\theta)$, $v(\theta)$, $\theta \in [0, t]$ can be presented in the forms, respectively:

$$x(t)=e^{A_1 t}x_0+\int_0^t e^{A_1(t-\theta)}f_1(u(\theta))d\theta+\lambda\int_0^t e^{A_1(t-\theta)}\left(\int_0^\theta K(\theta,s)x(s)ds\right)ds,$$

$$y(t)=e^{A_2 t}x_0+\int_0^t e^{A_2(t-\theta)}f_2(v(\theta))d\theta+\mu\int_0^t e^{A_2(t-\theta)}\left(\int_0^\theta L(\theta,s)y(s)ds\right)ds.$$

Let us interchange, by virtue of the Dirichlet rule [25], the order of integration in the last terms of the both expressions. Then we obtain

$$\int_0^t e^{A_1(t-\theta)}\left(\int_0^\theta K(\theta,s)x(s)ds\right)d\theta=\int_0^t\left(\int_s^t e^{A_1(t-\theta)}K(\theta,s)d\theta\right)x(s)ds,$$

$$\int_0^t e^{A_2(t-\theta)}\left(\int_0^\theta L(\theta,s)y(s)ds\right)d\theta=\int_0^t\left(\int_s^t e^{A_2(t-\theta)}L(\theta,s)d\theta\right)y(s)ds.$$

Thus, we come to the linear integral Volterra equations of second order

$$x(t)=\lambda\int_0^t K(t,s)x(s)ds+g_1(t), \tag{13}$$

$$y(t)=\mu\int_0^t \hat{L}(t,s)y(s)ds+g_2(t). \tag{14}$$

Here

$$g_1(t)=e^{A_1 t}x_0+\int_0^t e^{A_1(t-\theta)}f_1(u(\theta))d\theta, \tag{15}$$

$$g_2(t)=e^{A_2 t}y_0+\int_0^t e^{A_2(t-\theta)}f_2(v(\theta))d\theta, \tag{16}$$

$$\hat{K}(t,s)=\int_0^t e^{A_1(t-\theta)}K(\theta,s)d\theta,$$

$$\hat{L}(t,s)=\int_0^t e^{A_2(t-\theta)}L(\theta,s)d\theta.$$

Using the method of successive approximations [26] one can find solutions to the equations (13), (14):

$$x(t)=\lambda\int_0^t \hat{R}_1(t,s;\lambda)g_1(s)ds+g_1(t), \tag{17}$$

$$y(t)=\mu\int_0^t \hat{R}_2(t,s;\mu)g_2(s)ds+g_2(t), \tag{18}$$

where $\hat{R}_1(t,s;\lambda)$ and $\hat{R}_2(t,s;\mu)$ are the resolvents of the integral equations (13), (14), defined by the Neumann rows

$$\hat{R}_1(t,s;\lambda)=\sum_{i=1}^{\infty}\lambda^{i-1}\hat{K}_i(t,s), \tag{19}$$

$$\hat{R}_2(t,s;\lambda)=\sum_{i=1}^{\infty}\mu^{i-1}\hat{L}_i(t,s). \tag{20}$$

These rows are absolutely converging and the iterated kernels $\hat{K}_i(t,s)$, $\hat{L}_i(t,s)$, $i=1,2,...$ are given by the recursive formulas:

$$\hat{K}_1(t,s)=K(t,s),\ \hat{K}_i(t,s)=\int_s^t \hat{K}_1(t,\varsigma)\hat{K}_{i-1}(\varsigma,s)d\varsigma,$$

$$\hat{L}_1(t,s)=L(t,s)\ \hat{L}_i(t,s)=\int_0^t \hat{L}_1(t,\varsigma)\hat{L}_{i-1}(\varsigma,s)d\varsigma,\ i=2,....$$

Let us substitute formulas (15), (16) for $g_1(t)$ and $g_2(t)$ into the expressions (17), (18). Then we have

$$x(t)=e^{A_1t}x_0+\int_0^t e^{A_1(t-\theta)}f_1(u(\theta))d\theta+\lambda\int_0^t \hat{R}_1(t,s;\lambda)e^{A_1s}ds\cdot x_0+$$

$$+\lambda\int_0^t \hat{R}_1(t,s;\lambda)\left(\int_0^s e^{A_1(s-\theta)}f_1(u(\theta))d\theta\right)ds,$$

$$y(t)=e^{A_2t}y_0+\int_0^t e^{A_2(t-\theta)}f_2(v(\theta))d\theta+\mu\int_0^t \hat{R}_2(t,s;\mu)e^{A_2s}ds\cdot y_0+$$

$$+\mu\int_0^t \hat{R}_2(t,s;\mu)\left(\int_0^s e^{A_2(s-\theta)}f_2(v(\theta))d\theta\right)ds.$$

Upon application of the Dirichlet formula in the last terms of the above expressions we obtain

$$x(t)=\left(e^{A_1 t}+\lambda\int_0^t \hat{R}_1(t,s;\lambda)e^{A_1 s}ds\right)x_0+$$
$$+\int_0^t\left(e^{A_1(t-\theta)}+\lambda\int_\theta^t \hat{R}_1(t,s;\lambda)e^{A_1(s-\theta)}ds\right)f_1(u(\theta))d\theta, \tag{21}$$

$$y(t)=\left(e^{A_2 t}+\mu\int_0^t \hat{R}_2(t,s;\mu)e^{A_2 s}ds\right)y_0+$$
$$+\int_0^t\left(e^{A_2(t-\theta)}+\mu\int_\theta^t \hat{R}_2(t,s;\mu)e^{A_2(s-\theta)}ds\right)f_2(v(\theta))d\theta. \tag{22}$$

With the use of notations

$$\Phi_1(t,\theta)=e^{A_1(t-\theta)}+\lambda\int_\theta^t \hat{R}_1(t,s;\lambda)e^{A_1(s-\theta)}ds, \tag{23}$$

$$\Phi_2(t,\theta)=e^{A_2(t-\theta)}+\mu\int_\theta^t \hat{R}_2(t,s;\mu)e^{A_2(s-\theta)}ds, \tag{24}$$

the solutions to equations (11), (12) can be presented in explicit form:

$$x(t)=\Phi_1(t,0)x_0+\int_0^t \Phi_1(t,\theta)f_1(u(\theta))d\theta, \tag{25}$$

$$y(t)=\Phi_2(t,0)y_0+\int_0^t \Phi_2(t,\theta)f_2(v(\theta))d\theta. \tag{26}$$

Let us pass from the game under study (11), (12) to the equivalent game with the origin as the terminal set and the state vector $z=y-x$, evolving in $R^n$ according to (1), with

$g(t)=\Phi_2(t,0)-\Phi_1(t,0)$, $f_1(t,\theta,u(\theta))=\Phi_1(t,\theta)u(\theta)$, $f_2(t,\theta,v(\theta))=\Phi_2(t,\theta)v(\theta)$,

and starting from the initial state

$$z_0=y_0-x_0.$$

Then Conditions 3, 4 and Theorem2 reduce to the Conditions 6, 7 and Theorem 4, respectively.

**CONDITION 6.** The set-valued mapping

$$W(t,\theta)=\Phi_1(I(t),\theta)f_1(U) \overset{*}{-} \Phi_2(I(t),\theta)f_2(V)\neq\varnothing$$

has nonempty images at all $0 \le \theta \le t < +\infty$.

**CONDITION 7.** There exists function of time stretching $I(t)$, such that the set-valued mapping

$$W(t,\theta)=\Phi_1(I(t),I(t)-\theta)f_1(U) \overset{*}{-} \dot{I}(t)\Phi_2(I(t),I(t)-I(\theta))f_2(V)$$

has nonempty images at all $0 \le \theta \le t < +\infty$.

**Theorem 4.** Let the parameters of pursuit game (11), (12) meet Condition7 and let for the given initial states $x_0$, $y_0$ there exist a finite moment $t_1$,

$$t_1 = t_1(x_0, y_0) =$$

$$\left\{\min t : t \ge 0, \left( \Phi_2(I(t),0)y_0 - \Phi_1(I(t),0)x_0 - \int_0^{I(t)-t} \Phi_1(I(t),\theta)f_1(U)d\theta \right) \right. \tag{27}$$

$$\left. \cap \int_0^t W(t,\theta)d\theta \neq \varnothing \right\}.$$

Then the pursuer can terminate the game at the moment of time $I(t_1)$ for arbitrary admissible control of the evader.

Note that in the course of pursuit, beginning from the moment $\tau_0 = I(t_1) - t_1$, the pursuer constructs its current control on the basis of the evader's control on the time $I(t_1-\theta)-(t_1-\theta)$ earlier, defined by the formula:

$$\Phi_1(I(t_1),\tau_0+\theta)f_1(u(\tau_0+\theta)) =$$

$$= \dot{I}(t_1-\theta)\Phi_2(I(t_1),I(t_1)-I(t_1-\theta))f_2(v(I(t_1)-I(t_1-\theta))) + w(t_1,t_1-\theta)$$

$$\theta \in [0,t_1].$$

## ILLUSTRATIVE EXAMPLE OF INTEGRO-DIFFERENTIAL PURSUIT GAME

Let us consider the game, in which motions of the pursuer and the evader in $R^n$ are described by the equations, respectively [27]:

$$\dot{x}(t) = \lambda \int_0^t x(s)ds + u,\ u \in U,\ x(0) = x_0,\ \ \|u\| \le \rho, \tag{28}$$

$$\dot{y}(t) = \mu \int_0^t y(s)ds + v,\ v \in V, y(0) = y_0,\ \ \|v\| \le \sigma. \tag{29}$$

It is a particular case of the game (11), (12). We see that in the game under study $K_1(t,s)$, $K_2(t,s)$ are the unit matrices and $A_1$, $A_2$ — zero matrices. Using formulas for the iterated kernels one can easily evaluate

$$\hat{K}_1(t,s) = (t-s)E\,,\ \hat{L}_1(t,s) = (t-s)E\,.$$

Let us denote

$$\omega_1 = \sqrt{-\lambda}\,, \omega_2 = \sqrt{-\mu}\,.$$

In view of formulas (19), (20), the resolvents of the equations (28), (29), have the forms, respectively:

$$\hat{R}_1(t,s) = \frac{1}{\omega_1}\sin\omega_1(t-s)\,, \hat{R}_2(t,s) = \frac{1}{\omega_2}\sin\omega_2(t-s)\,, \text{ if } \lambda < 0\,,\ \mu < 0\,,$$

$$\hat{R}_1(t,s) = \frac{1}{\omega_2} sh\omega_2(t-s)\,, \hat{R}_2(t,s) = \frac{1}{\omega_1} sh\omega_1(t-s)\,, \text{ if } \lambda > 0\,,\ \mu > 0\,.$$

Then, by formulas (23), (24)

$$\Phi_1(t,\theta) = \begin{cases} \cos\omega_1(t-s)\cdot E & \text{if } \lambda < 0 \\ ch\omega_1(t-s)\cdot E & \text{if } \lambda > 0, \end{cases}$$

$$\Phi_2(t,\theta) = \begin{cases} \cos\omega_2(t-s)\cdot E & \text{if } \mu < 0 \\ ch\omega_2(t-s)\cdot E & \text{if } \mu > 0. \end{cases}$$

Here $E$ is $n$-dimensional unit matrix.

Let us analyze Condition 6 for various combinations of $\lambda$ and $\mu$ signs:

1) $\lambda < 0, \mu > 0$. Condition 6 reduces to the form:

$$\rho|\cos\omega_1 t| - \sigma|ch\omega_2 t| \ge 0\,.$$

This inequality is not fulfilled for all $t \ge 0$, therefore Condition 6 does not hold. The principle of the time stretching is not applicable because

$$ch\omega_2 t = \frac{e^{\omega_2 t} + e^{-\omega_2 t}}{2} \to +\infty \text{ as } t \to +\infty\,.$$

2) $\lambda > 0$, $\mu < 0$. Condition 6 has the form:

$$\rho|ch\omega_1 t| - \sigma|\cos\omega_2 t| \ge 0 \quad \forall t \ge 0\,.$$

It holds if $\rho \ge 2\sigma$.

3) $\lambda > 0$, $\mu > 0$. Condition 7 has the form:

$$\rho|ch\omega_1 t| - \sigma|ch\omega_2 t| \geq 0 \quad \forall t \geq 0 .$$

It holds if $\rho \geq \sigma$ and $\omega_1 > \omega_2$.

4) $\lambda < 0$, $\mu = 0$. Condition 6 takes the form:

$$\rho|\cos\omega_1 t| - \sigma \geq 0 \ \ \forall t \geq 0 .$$

It does not hold and the time stretching is not applicable.

5) $\lambda = 0$, $\mu < 0$. Condition 6 reduces to the form:

$$\rho - \sigma|\cos\omega_2 t| \geq 0 \ \ \forall t \geq 0 .$$

It holds if $\rho \geq \sigma$.

6) $\lambda = 0$, $\mu > 0$. Condition 7 has form of the inequality $\rho - \sigma|ch\omega_2 t| \geq 0$ and does not hold $\forall t \geq 0$. The principle of the time stretching is not applicable since $ch\omega_2 t \to +\infty$ as $t \to +\infty$.

7) $\lambda > 0$, $\mu = 0$. Condition 6: takes the form $\rho|ch\omega_1 t| - \sigma \geq 0 \ \ \forall t \geq 0$ and holds if $\rho \geq \sigma$.

8) The case $\lambda < 0$, $\mu < 0$ presents special interest and is analyzed in detail. Condition 6 has the form:

$$\rho|\cos\omega_1 t| \cdot S \underline{*} \sigma|\cos\omega_2 t| \cdot S \neq \varnothing \ \ \forall t \geq 0 .$$

Here $S$, $S \in R^n$ is the ball of unit radius centered at the origin. Evidently, this condition does not hold.

Let us apply the time stretching principle. In the case under study Condition 7 (with the time stretching) looks as follows:

$$W_1(t) = \rho|\cos\omega_1 t| \cdot S \underline{*} \sigma\dot{I}(t)|\cos\omega_2 I(t)| \cdot S \neq \varnothing \ \ \forall t \geq 0 .$$

It is equivalent to the inequality

$$\rho|\cos\omega_1 t| - \sigma\dot{I}(t)|\cos\omega_2 I(t)| \geq 0 \quad \forall t \geq 0 . \tag{30}$$

Let us assume that

$$\omega_1 > \omega_2 \tag{31}$$

and let us select the function of time stretching

$$I(t) = \frac{\omega_1}{\omega_2} t .$$

Then the relation (30) reduces to the inequality:

$$\left(\rho-\sigma\frac{\omega_1}{\omega_2}\right)\left|\cos\omega_1 t\right|\geq 0\,. \tag{32}$$

We impose, in addition to the condition (31), following constraint on the game parameters:

$$\frac{\rho}{\omega_1}\geq\frac{\sigma}{\omega_2}\,. \tag{33}$$

It is easy to see that, under the conditions (31), (33), the inequality (32) holds for all $t\geq 0$, that means that Condition 7 is fulfilled.

Now we will show that assumption (27) of Theorem4 is satisfied for arbitrary initial states $x_0$, $y_0$ of the objects. To this end, we set control of the pursuer on the initial half-interval of time equal zero, that is $u^0(\theta)=0,\ \theta\in[0, I(t_1)-t_1)$. Then, in view of Theorem4, it remains to show that there exists an instant of time $t_1$, $0<t_1<+\infty$, at which the following inclusion is true:

$$\pi e^{I(t_1)A}z_0\in\int_0^{t_1}W_1(\theta)d\theta\,.$$

In the example under study this inclusion reduces to the form:

$$\cos\omega_2 I(t)y_0-\cos\omega_1 I(t)x_0\in\int_0^t\left(\rho\left|\cos\omega_1 t\right|-\sigma\dot{I}(t)\left|\cos\omega_2 I(t)\right|\right)d\theta\cdot S\,. \tag{34}$$

Substituting $I(t)=\frac{\omega_1}{\omega_2}t$ into the inclusion (34), we convert the latter into the relationship

$$\left\|\cos\omega_1 t\cdot y_0-\cos\frac{\omega_1^2}{\omega_2}t\cdot x_0\right\|\leq\left(\rho-\sigma\frac{\omega_1}{\omega_2}\right)\int_0^t\left|\cos\omega_1 t\right|d\theta\,.$$

One can readily see that the left-hand part of the above inequality is less or equal to $\|x_0\|+\|y_0\|$, while the right-hand part is more or equal to $\left(\rho-\sigma\frac{\omega_1}{\omega_2}\right)\cdot\left[\frac{t}{\pi/\omega_1}\right]$, where by symbol $[\cdot]$ is denoted the integer part of a number. That is why, there exists a moment of time $t_1$ at which this inequality is satisfied and, therefore, the inclusion (34) holds.

Hence, by virtue of Theorem 4, under the conditions (31), (33) on the game parameters, the pursuer can catch the evader at a finite moment of time, for arbitrary initial states of the players.

## CONCLUSION

An original approach is developed to study game dynamic problems of pursuit. It is applicable to a wide range of conflict-controlled functional-differential systems. In the paper, sufficient conditions for guaranteed capture are obtained in the case of integro-differential dynamics of objects. The time-stretching principle offers promise as an efficient tool for probing complicated problems of mobile objects conflict counteraction, for which classic condition for the instantantaneos advantage of the pursuer over the evader does not hold. Suggested approach makes it feasible to realize the process of pursuit with the help of appropriate counter-controls by Krasovskii.

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ПРИНЦИП РОЗТЯГУ ЧАСУ В ІГРОВИХ ЗАДАЧАХ ДИНАМІКИ

**Вступ.** Є широке коло процесів механіки, економіки і біології, які розвиваються в умовах конфлікту та невизначеності і можуть бути описані різного роду функціонально-диференційними системами залежно від природи процесу.

В роботі розглядаються динамічні ігри переслідування, які визначаються системою загального вигляду, яка охоплює широке коло функціонально-диференційних систем.

У дослідженні динамічних ігор вирішальним фактором є інформованість гравців про поточний стан процесу. У реальних системах інформація, як правило, надходить із запізненням у часі. Також, є низка ігрових завдань, для яких не виконується умова Понтрягіна, що відображає миттєву перевагу одного гравця над іншим в ресурсах керування. Встановлення тісного зв'язку між узагальненням цієї умови, пов'язаної з розтягуванням часу і ефектом змінного запізнювання інформації відкриває великі перспективи для розв'язання вищезазначених завдань.

**Мета статті** — на основі ефекту запізнювання інформації вивести достатні умови завершення гри, для якої є не виконаною умова Понтрягіна, конкретизувати їх на випадок інтегро-диференційної динаміки з подальшою ілюстрацією отриманого результату на модельному прикладі.

**Методи.** Для дослідження динамічної гри переслідування застосовується перший прямий метод Понтрягіна, що забезпечує приведення траєкторії конфліктно-керованого процесу на циліндрично термінальну множину в кінцевий момент часу. Водночас, побудова керування переслідувача здійснюється на основі теореми Філіппова-Каста про вимірний вибір, що забезпечує реалізацію процесу переслідування у класі стробоскопичних стратегій Хайєка. Для виведення рішення конфліктно-керованої інтегро-диференційної системи у формі Коші використовується метод послідовних апроксимацій.

**Результати.** Показано, що динамічна гра переслідування з розділеними блоками керування гравців і змінним запізненням інформації еквівалентна деякій грі з повною інформацією. На основі цього факту розроблено принцип розтягування часу для дослідження ігор з повною інформацією, для яких не виконано класичну умову Понтрягіна, що лежить в основі всіх прямих методів переслідування. У роботі пропонується модифікація цієї умови, пов'язана з розтягуванням часу, що дає змогу отримати достатні умови приведення траєкторії гри на термінальну множину в кінцевий момент часу. Описано спосіб побудови керування переслідувача, який приводить до досягнення мети.

Отримано конкретний вигляд цих умов для інтегро-диференційної гри переслідування. В якості ілюстрації проведено детальний аналіз конкретного прикладу інтегро-диференційної гри. Знайдено функцію розтягування часу, що забезпечує виконання узагальненої умови Понтрягіна. Виведено прості співвідношення між параметрами руху гравців і їхніми ресурсами керування, що забезпечують переслідувачеві можливість зловити гравців, які тікають, за будь-яких їхніх початкових положень.

**Висновки.** Рrозроблено ефективний засіб для аналізу конфліктних ситуацій, наприклад, перехоплення рухомої цілі керованим рухомим об'єктом. Проаналізовано ситуацію, коли об'єкт, який переслідує, не має миттєвої переваги у ресурсах керування перед гравцем, який тікає. Запропонований підхід дає змогу реалізувати процес переслідування за допомоги відповідних контр-керувань Красовського.

***Ключові слова:*** *динамічна гра, змінне запізнення інформації, умова Понтрягіна, інтеграл Ауманна, принцип розтягу часу, різниця Міньковського, інтегро-диференційна гра.*

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## ПРИНЦИП РАСТЯЖЕНИЯ ВРЕМЕНИ В ИГРОВЫХ ЗАДАЧАХ ДИНАМИКИ

***Введение.*** Существует широкий круг процессов механики, экономики и биологии, развивающихся в условиях конфликта и неопределенности, которые могут быть описаны различного рода функционально-дифференциальными системами в зависимости от природы процесса. В работе рассматриваются динамические игры преследования, определяемые системой общего вида, охватывающей широкий круг функционально-дифференциальных систем.

При исследовании динамических игр решающим фактором является информированность игроков о текущем состоянии процесса. В реальных системах информация, как правило, поступает с запаздыванием во времени. Также существует ряд игровых задач, для которых не выполняется условие Понтрягина, отражающее мгновенное преимущество одного игрока над другим в ресурсах управления. Установление тесной связи между обобщением этого условия, связанного с растяжением времени и эффектом переменного запаздывания информации, открывает большие перспективы для решения вышеупомянутых задач.

***Цель статьи*** **—** на основе эффекта запаздывания информации вывести достаточные условия завершения игры, для которой не выполнено условие Понтрягина, конкретизировать их на случай интегро-дифференциальной динамики с последующей иллюстрацией полученного результата на модельном примере.

***Методы.*** Для исследования динамической игры преследования применяется первый прямой метод Понтрягина, обеспечивающий приведение траектории конфликтно-управляемого процесса на цилиндрическое терминальное множество в конечный момент времени. При этом, построение управления преследователя осуществляется на основе теоремы Филиппова-Кастена об измеримом выборе, что обеспечивает реализацию процесса преследования в классе стробоскопических стратегий Хайека. При выводе решения конфликтно-управляемой интегро-дифференциальной системы в форме Коши используется метод последовательных аппроксимаций.

***Результаты.*** Показано, что динамическая игра преследования с разделенными блоками управлений игроков и переменным запаздыванием информации эквивалентна некоторой игре с полной информацией. На основе этого факта разработан принцип растяжения времени для исследования игр с полной информацией, для которых не выполнено классическое условие Понтрягина, лежащее в основе всех прямых методов преследования. В работе предлагается модификация этого условия, связанная с растяжением времени и позволяющая получить достаточные условия приведения траектории игры на терминальное множество в конечный момент времени. При этом описывается способ построения управления преследователя, приводящий к цели.

Получен конкретный вид этих условий для интегро-дифференциальной игры преследования. В качестве иллюстрации проведен подробный анализ конкретного примера интегро-дифференциальной игры. Найдена функция растяжения времени, обеспечивающая выполнение модифицированного условия Понтрягина. Выведены простые соотношения между параметрами движения игроков и их ресурсами управления, обеспечивающие преследователю возможность поймать убегающего при любых начальных положениях игроков.

***Выводы***. Разработано эффективное средство для анализа конфликтных ситуаций, например, перехвата подвижной цели управляемым движущимся объектом. Проанализирувана ситуация, когда преследующий объект не обладает мгновенным преимуществом в ресурсах управления перед убегающим игракой. Предлагаемый подход позволяет реализовать процесс преследования с помощью подходящих контр-управлений Красовского.

***Ключевые слова:*** *динамическая игра, переменное запаздывание информации, условие Понтрягина, интеграл Аумана, принцип растяжения времени, разница Минковского, интегро-дифференциальная игра*

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## SOFTWARE MODULE FOR PERSONAL DIAGNOSTICS OF MOTOR FUNCTIONS AFTER STROKE

***Introduction.*** *Diagnostics of motor functions after stroke plays an important role in the formation of a rehabilitation program. The results of the preliminary clinical trials of our proposed technique for quantitative assessment of motor functions deficit during studying the dynamics of movement restoring based on bio-informational technology of motor control TRENAR® confirmed the advisability of using this technique to create a new algorithmic and software tools for personal diagnostics of motor functions.*

***The purpose of the paper*** *is to develop a specialized module for the personal diagnostics of motor functions in patients after stroke, which software implements the determination of the degree of motor functions disorders and the results of their recovery using the technique for quantitative assessment of motor functions deficit.*

***Results.*** *The structural and functional model of the software module for personal diagnostics of motor functions and the effectiveness of their recovery as a result of rehabilitation measures in patients after stroke has been developed.*

*An algorithm for diagnostic the motor functions disorder degree of the affected limbs in patients after stroke and the activity diagram of software module using Unified Modeling Language (UML) are presented.*

*The software module "Movement Test Stroke" has been made in Visual Studio 2013 software environment. The programming language is C#. The module is installed in the PC structure.*

*Diagnostic benefits: the ability to obtain an integrated quantitative assessment of the motor functions deficit of the upper and lower limb at the level of separate joints, hand or walking according to relevant evidential criteria, and assessment of muscle hyper- or hypotone at different stages of rehabilitation. The advantage of diagnostics is that the motor func-*

*tions disorder degree is performed relative to the patient's own healthy limbs, the motor functions of which characterize the individual norm of disorders absence.*

***Conclusions.*** *The quantitative assessment of motor function deficit by evidential criteria, which is provided by the software module "Movement Test Stroke" is the basis to synthesize the digital health mobile means for information and advisory assistance to the physician in creating and making adjustments to personal plan for recovery the motor functions affected by pathology at different stages of stroke rehabilitation.*

***Keywords:*** *software module, structural and functional model, diagnostics, algorithm, motor functions, personal quantitative assessment, stroke.*

## INTRODUCTION

For many years, stroke has been ranked 2$^{nd}$ in the list of major causes of disability and death in the world and in Ukraine. Stroke is one of the most common causes of functional failure. This disease may cause impairment or loss of motor functions, vision, speech and mental functions. Of particular concern is the increasing burden of stroke among people of working age: more than 50% of those who survived stroke never return to work. In Europe, an action plan to combat stroke during 2018–2030 has been approved. [1]. In Ukraine the creation of modern centers for the treatment of strokes according to European standards is also provided.

The main goal of the rehabilitation process is associated with person's reserves mobilization that is adequate to his state to restore damaged or lost functions. When restoring motor functions, the mobilization of reserves provides for the development and implementation of individual comprehensive programs of medical rehabilitation, in which along with drugs, electrical myoneurostimulation especially programmed stimulation occupies a significant place, as a way to force muscle contraction according to certain programs. To determine the control action — an individual program for the rehabilitation of motor functions — the rehabilitologist should have a wide range of training programs and methods, among which he can choose the one that is most appropriate for the state and stage of patient rehabilitation. This approach allows the implementation of a new bioinformation technology for the restoration of motor functions TRENAR®, which is realized by portable electronic devices Trenar-01 and Trenar-02 [2].

The range of programs in these devices is represented for training the forced muscle contractions: 1) by synthesized electromyostimulation programs — ***the program*** "SYNTHESIS"; 2) by programs that are "read" from the patient's own healthy muscles or muscles of another person (instructor) during their voluntary contractions and transmitted to the training muscles online — ***the program*** "DONOR"; 3) for training the ratio of voluntary and forced contractions of the muscles under the threshold electromyostimulation method, when voluntary, even minor, contractions of the training muscles, under the condition of overcoming a certain threshold of the EMG signal, automatically "start" the electrostimulation of the same muscle to achieve a certain value of muscle contraction — ***the program*** "THRESHOLD"; 4) for training voluntary and forced muscles contractions in recording-reproducing mode, when EMG signal of arbitrarily contracted muscle is recorded in the memory of device and transformed into electrical stimulation program of the same muscle that is being trained — ***the program*** "MEMORY-Auto"; 5) for training voluntary muscles contractions by the BIOFEEDBACK method (visual and auditory) by electromyogram — ***the program*** "BIOTRAINING" [2, 3].

A common benefit of these training programs is the combination *of physical and cognitive effects* that trigger and stimulate the person's reserves to restore movements. However, each program has personal advantages that determine the feasibility of its use, depending on the state of motor functions, the general neurological status of the patient and the stage of rehabilitation.

## PROBLEM STATEMENT

The use of technology TRENAR® in restorative motion therapy has shown a significant percentage of improvements in locomotor functions, which in particular, after stroke, reaches 93%. These results provide the basis for incorporation the technology TRENAR® into the mandatory set of measures aimed at restoring motor functions. However, the success of the extensive use of innovative technology TRENAR® is largely determined by the objective evaluation of the effectiveness of the rehabilitation process based on the quantitative assessment of the motor function disorder degree of patient at different recovery periods after stroke.

As a result of previous studies, a new technique for quantitative assessment of motor functions deficit (motor disorders depth) in patients after stroke has been developed. This technique is based on expert evaluation according to the main and additional evidential criteria [4]. The main features of the technique are:

– a separate quantitative assessment of the motor functions deficit of the affected lower and upper limbs, their proximal and distal departments, according to the main criteria, on the basis of which an integral quantitative assessment of global movements disorders is formed;

– introduction of additional criteria for hand assessing (including fine motor skills) and form of walking;

– determination of the individual norm of disorders absence: expert assessing of the affected limbs is carried out in relation to the patient's own healthy limbs, the motor functions of which characterize the individual norm of disorders absence;

– unification of quantitative assessment of the disorders degree: all quantitative scales for all criteria have the same six-point gradation.

The developed technique has undergone preliminary clinical testing during studies of the dynamics of movement restoration after stroke with the new technology of training / restoration of movement functions TRENAR®. The results of the trial confirmed the benefits of the technique and appropriateness of its use in clinical practice.

**The purpose** of the paper is to develop a specialized module for the personal diagnosis of motor functions in patients after a stroke, which software implements the determination of the degree of motor functions impairment and the results of their recovery using the new method of personal quantitative assessment of motor function deficiency.

## STRUCTURAL AND FUNCTIONAL MODEL OF THE SOFTWARE MODULE FOR THE DIAGNOSTICS THE DEGREE OF MOTOR FUNCTIONS DISORDERS IN PATIENTS AFTER STROKE

The Protocol with the relevant tables for assessing the motor disorders for the convenience of using by neurologists a new technique for quantitative assessment of movement disorders degree in patients after stroke by TRENAR® technology has been developed:

*Table. 1.* **The muscle strength and movements' volume assessing**

| **Grade** | **The muscle strength of the affected limb** | Ratio (affected / healthy muscle),% | **Movements' volume reference** |
|---|---|---|---|
| **5** | Full motion during gravity with maximum external counteraction | 100 | Movements' volume is full, tempo isn't reduced |
| **4** | Full motion during gravity and with little external counteraction | 75 | Movements' volume is 75-100 % of norm; strength, agility, tempo are reduced |
| **3** | Full motion during gravity only | 50 | Movements' volume is 50-75 % of norm, inept |
| **2** | Full motion in unloading conditions | 25 | Movements' volume is 25-50 % of norm |
| **1** | A feeling of tension during the attempt of voluntary movement | 10 | Movements' volume is up to 25 % of normal, is extremely restricted |
| **0** | Absence of tension signs during the attempt of voluntary movement | 0 | No active movements |

*Table. 2.* **The motor functions of the upper and lower limbs by additional criteria assessing**

| Grade | Upper limb (hand) | | | Lower limb (walking) |
|---|---|---|---|---|
| | Contrasting the thumb | Flexing of fingers in fist | The main hand's motor function | Form of walking |
| 5 | Reaches the base of all fingers | Full flexing | Function is saved | No change |
| 4 | Reaches the base of all fingers (without holding the base) | Full flexing (without holding) | Capturing and holding the items are saved, capturing the small items is available (with no hold function) | While walking limping by the paretic leg |
| 3 | Reaches the base of 4-th finger | Slight flexing limitation of distal phalanges to thenar | Holding the items is available, capturing the small items is complicated | Hemiparetic walking (patient pulls leg) |
| 2 | Reaches the base of 3-rd finger | Moderate limitation of distal phalanges to thenar | Capturing the large items without their long and strong holding is available | Circulating or hemiplegic walking |
| 1 | Reaches the base of 2-nd finger | Significant limitation of distal phalanges to thenar | Capturing and holding both large and small items are impossible; the additional function of supporting and pressing the item is saved | Roughly broken walking, several steps with support or crutches |
| 0 | Contrasting is impossible | Fingers flexing is impossible | Capturing and holding the items are impossible | Doesn't go alone |

– on the main evidential criteria the proximal and distal departments for upper and lower limbs on the level of joints have been estimated (2 criteria: muscle strength [5] and movements' volume [6] on generally accepted six-grades scales (Tab. 1));

– on the additional evidential criteria walking (1 criterion) and hand (3 criteria) have been estimated [7 with authors' correction].

The tables of the summary quantitative characteristics of movement disorders and paresis degree linked with paresis degree (Tab. 3) as well as effectiveness of motor functions restoring (Tab. 4) are also added to the Protocol.

All quantitative assessment scales have the same six-point gradation on all criteria with the same orientation from the best indicator (5 grades, no disorders) to the worst (0 points, plegia) linked to paresis degree: severe — 1 grade, major — 2 grades, moderate — 3 grades, l mild — 4 grades.

The quantitative assessment of the hand's motor functions deficit is of particular importance during a focused training of fine motor skills to restore the speech. This makes it possible to study and compare the restoration dynamics of fine motor movements of affected hand with speech restoration dynamics in motor or motor-sensory aphasia after a stroke.

The walking assessment on additional criteria (Tab. 2) is of big importance because it adds to muscle functions characteristics of affected lower limb at level of different joints such an important characteristic as walking movements coordination.

The formation of the quantitative integral assessment of motor disorders degree at level of the joints (Tab. 3) makes it possible to create a more accurate gradation of motor functions restoration and reduce the expert evaluation error in subjective assessment.

*Table. 3.* **The summary quantitative characteristics of movement disorders depth in different parts of the upper and lower limbs**

| **TOTAL ASSESSMENT IN GRADES BY CRITERIA** | | | | | | |
|---|---|---|---|---|---|---|
| ***Global Movements***<br>***Joints of upper limb departments*** *proximal: shoulder, elbow ;distal: wrist*<br>***Lower limb departments*** *proximal: hip, knee; distal: ankle* | | | | | | |
| **Grades** | 0 | 1 – 2 | 3 – 4 | 5 – 7 | 8 – 9 | 10 |
| **Paresis degree** | plegia | severe | major | moderate | mild | no disorders |
| ***Hand (including fine motor skill)*** | | | | | | |
| **Grades** | 0 | 1 – 3 | 4 – 6 | 7 – 9 | 10 – 14 | 15 |
| **Paresis degree** | plegia | severe | major | moderate | mild | no disorders |
| ***Walking*** | | | | | | |
| **Grades** | 0 | 1 | 2 | 3 | 4 | 5 |
| **Paresis degree** | plegia | severe | major | moderate | mild | no disorders |

The quantitative assessment of effectiveness is shown through the difference in grades before and after rehabilitation obtained at the level of limb's joint, hand or walking linked with reference to a verbal assessment (effectiveness gradation) (unchanged, minor improvements, improvements, major improvements) for two, three and one criterion according to formula $\Delta = \Delta_2 - \Delta_1$, where $\Delta_1$ — grades before rehabilitation, $\Delta_2$ — grades after rehabilitation, $\Delta$ — grades difference, which shows the rehabilitation effectiveness.

The distribution of effectiveness gradations for the relevant joints, hand or walking is shown in Table 4.

Aside movement disorders also are estimated by criterion of muscle hypertone (on generally accepted Ashworth scale) [6] (Tab. 5) and by criterion of muscle hypotone (on new scale) (Tab. 6). As the muscle tone in post-stroke patients can vary from hypo to hypertonus, each with its gradation, this criterion is not included in the integral quantitative characteristics of movement disorders. Meanwhile, the quantity of hypertone and hypotone is of diagnostic value in the creation of myoneurostimulation programs of individual rehabilitation plan in patients after stroke. On the basis of the Protocol (Fig. 1) with the relevant tables (Tab. 1–6), the structural and functional model of the software module for the motor function disorders degree diagnostics in patients after stroke has been developed (Fig. 2).

The software module for the motor function disorders degree diagnostic in patients after stroke consists of a graphical interface and the objects of the program module (units): general information, motor functions assessment, instructions, database, information processing and results.

*Table. 4.* **The effectiveness of motor functions restoring**

| **Grades of movement rehabilitation effectiveness** | ***The quantity of movement rehabilitation effectiveness***, Δ grades | | |
|---|---|---|---|
| | *Global Movements (2 criteria)* | *Hand (3 criteria)* | *Walking (1 criterion)* |
| Major improvement | 5 – 10 | 7 – 15 | 3 – 5 |
| Improvement | 3 – 4 | 4 – 6 | 2 |
| Minor improvement | 1 – 2 | 1 – 3 | 1 |
| Unchanged | 0 | 0 | 0 |

*Table. 5.* **The muscle hypertone of the affected limb assessing**

| **Grades** | ***Muscle hypertone reference (on the conventional Ashforth scale)*** |
|---|---|
| **0** | No changes in muscle tone |
| +1 | Slight increase in muscle tone, manifested during flexion / extension the affected limb part by minimal resistance at the end of the range of motion |
| +2 | Slight increase in muscle tone, manifested by resistance that appears after not less than half of the range of motion performance |
| +3 | Mild increase in muscle tone, manifested by through all range of motion but doesn't complicate the performance of passive movements |
| +4 | Major increase in muscle tone, which complicates performance of passive movements |
| +5 | Affected limb part fixed in flexion or extension - spasticity. Movements are impossible |

*Table. 6.* **The muscle hypotone of the affected limb assessing**

| Grades | *Muscle hypotone reference (new scale)* |
|---|---|
| **0** | No changes in muscle tone |
| **-1** | Slight reduction of muscle tone. Voluntary movements are possible 75 % of norm (75 % of full range of motion). The patient may hold the affected limb in a flexion / extension position during passive movements. |
| **-2** | Slight decrease in muscle tone. Voluntary movements are possible 50 % of norm (up to half of full range of motion). The patient may hold the affected limb in a flexion / extension position during passive movements. |
| **-3** | Mild decrease in muscle tone. Arbitrary Voluntary movements are possible 25 % of norm. The patient can hold the affected limb in a flexion / extension position during passive movements, but for a short time. |
| **-4** | Major decrease in muscle tone. Voluntary movements are possible 10 % of norm. The patient can't hold the affected limb in the flexion / extension position during passive movements. |
| **-5** | There is no muscle tone. Voluntary movements are impossible. The patient can't hold the affected limb in the flexion / extension position during passive movements. Atonia |

The operator interacts directly with the Graphical user interface (GUI), which provides a dialog mode, captures motor function indicators by the testing results. The GUI also provides interconnecting and compatible functioning of software blocks.

The *general information unit* (Fig. 2) contains object-oriented programming (OOP) methods that introduce general patient's information according to the Protocol (Fig. 1). The information from this unit goes to the *processing unit* for its further storing in the *buffer* of *processing unit* and in the *database*.

The *instructions unit* contains:

– a toolkit that is the a structured, matrix-organized information for dialogue windows presenting for assessing the limbs motor function at the level of the selected joints, hand or walking, and the results of their quantitative evaluation on the PC screen;

– control codes to provide access to the toolkit for different OOP methods.

The toolkit and control codes goes from the *instructions unit* to the *motor function assessment unit*, the *processing unit* and *results unit.*

The *motor function assessment unit* contains OOP methods to fix by the operator the motor functions indicators of upper and lower limbs, their proximal and distal departments at the level of joints, hand and form of walking, and for transmission the fixed motor functions indicators to *processing unit*. This unit is functionally separated, i.e. motor functions disorders of limbs' joints, hand and form of walking are being assessed separately.

The *processing unit* contains a buffer for temporary storage of variables that used during program performance (which simplifies the program as a whole), methods of forming appropriate windows for assessing the motor functions, methods of forming the electronic medical record (EMR) (Fig. 2), methods for determining the paresis degree.

From the *processing unit* the information goes to the *results unit*.

The *results unit* presents information on the quantitative evaluation of motor functions assessment of selected limbs' joints, hand or form of walking by the criteria, and integrated quantitative assessment of its deficit and paresis degree on the PC screen.

**Protocol for assessing the motor functions disorders degree of limbs**
**in patients after stroke and the movements rehabilitation efficiency by TRENAR® technology**

**Full name** ____________________, **Medical record №**________,
sex (male, female), age _____, height ________, weight ______
**Rehab start date** __ / __ / ____ ., **Rehab complete date** __ / _ / ___.
**Diagnosis, date** ________________________________________
________________________________________

**Rehab period:** acute; early phase, late phase; residual
**Motor signs of disease**: hemiparesis, monoparesis (upper, lower)
**Paresis side**: left, right
**Speech signs of disease**: motor, sensory, sensory-motor aphasia, dysarthria, dystonia, etc.
**Related diseases** ________________________________________

*THE ANALYSIS OF GLOBAL MOVEMENTS DISORDERS OF LIMBS' MOTOR FUNCTIONS*

| ***Criteria for assessment the global movements disorders of limbs' motor functions*** | Upper Limb departments | | | | | | Lower Limb departments | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Proximal department | | | | Distal department | | Proximal department | | | | Distal department | |
| | Shoulder joint | | Elbow joint | | Wrist joint | | Hip joint | | Knee joints | | Ankle joint | |
| | *Before* | *After* | *Before* | *After* | *Before* | *After* | *Before* | *After* | *Before* | *After* | *Before* | *After* |
| ***Criterion 1.*** The muscle strength, in grades (tab. 1) | | | | | | | | | | | | |
| ***Criterion 2.*** Movements' volume, in grades (tab. 1) | | | | | | | | | | | | |
| ***Criterion 3.*** Muscle tone, in grades (*tab. 5, 6*) | | | | | | | | | | | | |
| **TOTAL (sum of crit. 1 and crit. 2),** in grades | | | | | | | | | | | | |
| **The paresis degree** (total grades) (*tab. 3*) | | | | | | | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Δ* (the efficiency value), in grades | | | | | | |
| The rehab efficiency grade (*tab. 4*) | | | | | | |

* Δ - the **difference** between the results **after** and **before** rehabilitation.

*THE ANALYSIS OF THE HAND DISORDERS*

| ***Criteria for assessment the hand disorders*** | *Before* | *After* |
|---|---|---|
| ***Criterion 1.*** Contrasting the thumb, in grades (*tab. 2*) | | |
| ***Criterion 2.*** Flexing of fingers in fist, in grades (*tab. 2*) | | |
| ***Criterion 3.*** The main hand's motor function, in grades (*tab. 2*) | | |
| **TOTAL (sum of all criteria),** in grades | | |
| **The paresis degree** (total grades) (*tab. 3*) | | |

| | |
|---|---|
| Δ* (the efficiency value), in grades | |
| The rehab efficiency grade (*tab. 4*) | |

*THE ANALYSIS OF THE WALKING DISORDERS*

| ***Criteria for assessment the walking disorders*** | *Before* | *After* |
|---|---|---|
| Form of walking (*tab. 2*) | | |
| **TOTAL,** in grades | | |
| **The paresis degree** (*tab. 3*) | | |

| | |
|---|---|
| Δ* (the efficiency value), in grades | |
| The rehab efficiency grade (*tab. 4*) | |

**Conclusions on the rehab course:** ________________________________________

**Program of motor functions trainings**: Electrostimulation (Synthesis, Donor, Threshold stimulation), Biotraining, without trainings

Training movements ________________________________________

Additional rehabilitation measures ____________________

Number of rehab sessions (scheduled / completed) __ / __
Medicament correction ____________________

Other ____________________

***Fig. 1.*** Protocol for assessing the motor functions disorders degree of limbs in patients after stroke and the movements' rehabilitation efficiency by TRENAR® technology

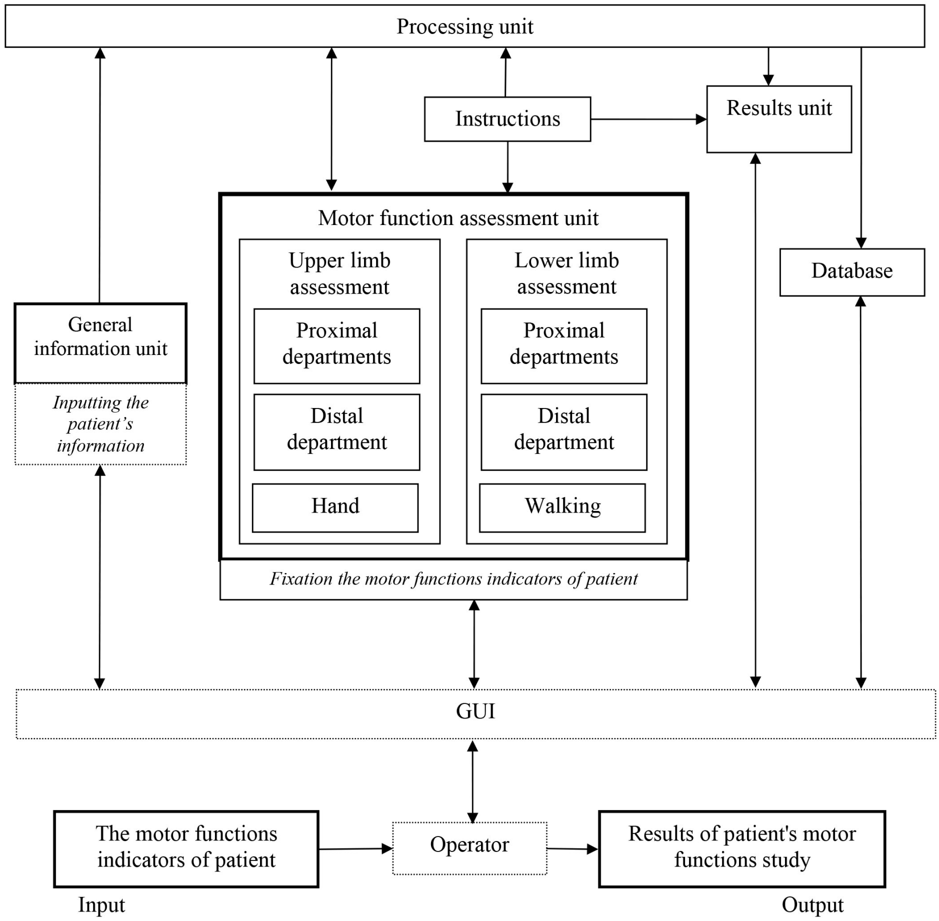


***Fig. 2.*** Structural and functional model of the software module for the motor function disorders degree diagnostics in patients after stroke

The *database* is presented in the form of an electronic medical record (form 003 / o "Medical card of the in-patient"), which contains both general information about the patient and the results of the patient's motor functions testing.

## THE ALGORITHM FOR DIAGNOSTICS THE MOTOR FUNCTIONS DISORDER DEGREE IN PATIENTS AFTER STROKE

The algorithm for diagnosing the motor functions disorder degree of limbs in patients after stroke (according to the technique for quantitative assessment of motor functions deficit) is presented on Fig. 3.

The software module "Movement Test Stroke", which implements this algorithm, is made in Visual Studio 2013 software environment. The programming language is C#. It is installed in the PC structure.

The activity diagram of the software module for diagnostics the motor functions disorder degree on the basis of unified modeling language (UML) [8] is shown on Fig. 4 and consists of stages (Fig. 4):

– Inputting the patient's information into the general information unit.
– Selecting the relevant joint, hand or walking for motor functions assessing.
– Motor functions assessing of selected joints of proximal or distal departments of upper or lower limbs; hand or form of walking according to appropriate criteria and calculation of the paresis degree.
– The diagnostics results review of motor functions disorder degree.
– Saving the diagnostics results to the electronic medical record.
– End the patient's diagnostics session.

On the diagram (Fig. 4) the nodes of solutions and associations ("diamonds", Fig. 4), which are an analog to the logical function "OR", synchronization lines, which are an analog to the logical function "AND", initial and final activity nodes (appropriately "Getting Started" and "End the Session", Fig. 4) according to the UML notation are located [8, 9].

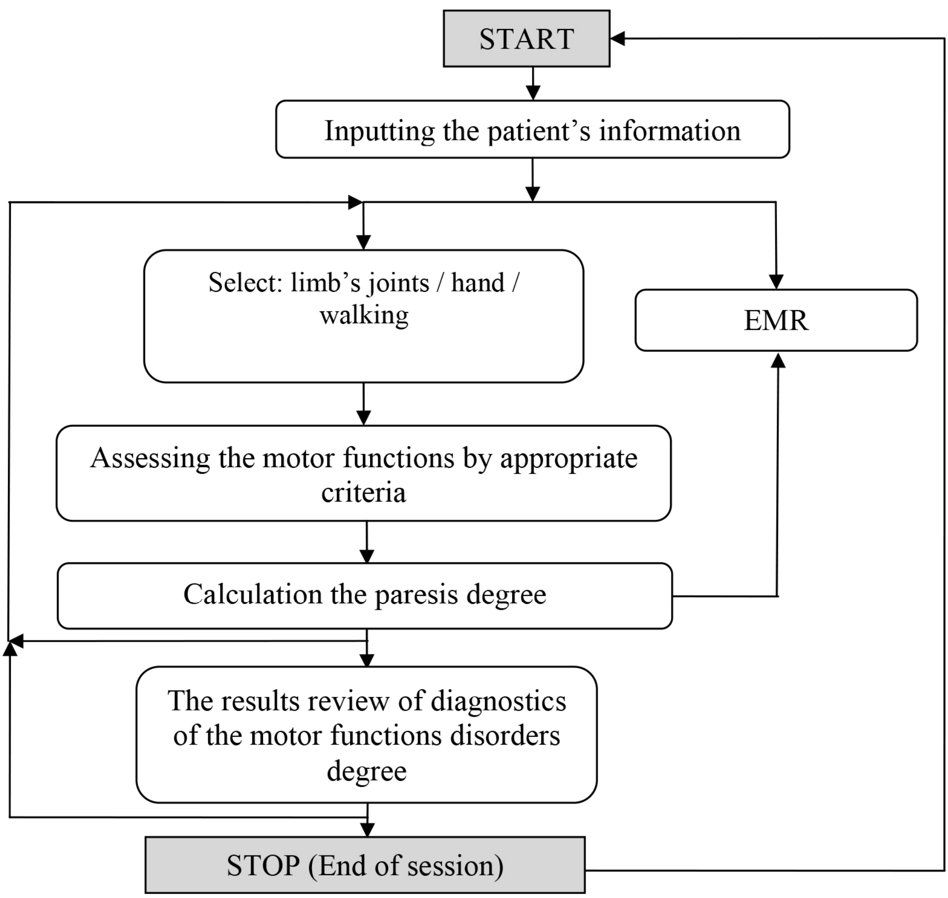


***Fig. 3.*** Algorithm for diagnosing the motor functions disorder degree in patients after stroke

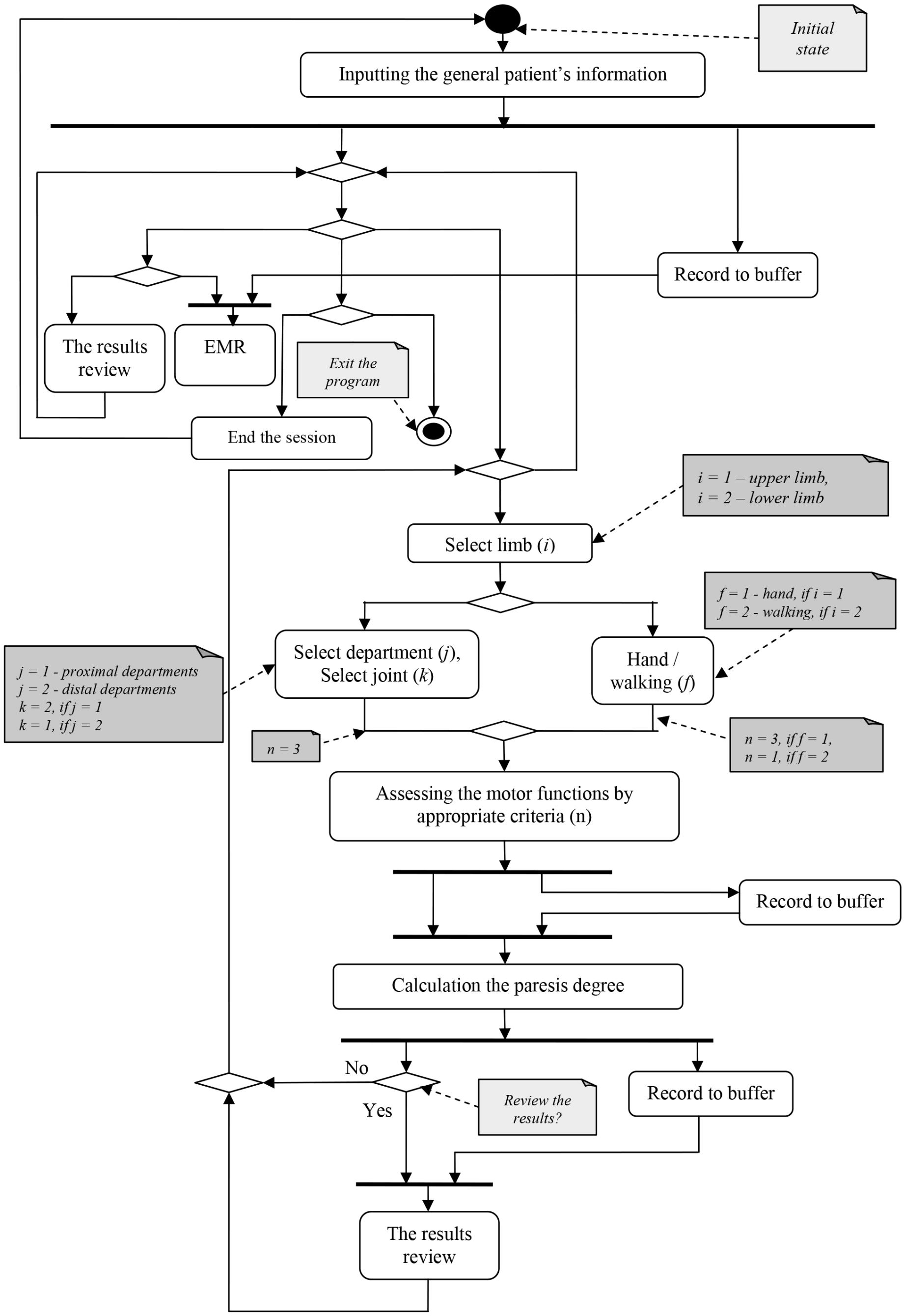


***Fig. 4.*** Activity diagram of the software module of motor functions disorder degree diagnostics in patients after stroke

The software consequentially implements the following actions:

1. Introduction of general patient's information. This information is stored in a buffer for future use and for storing in an electronic medical record (EMR).

2. Transition to the interface window of the motor functions assessment. The physician can carry out full testing - consequentially from the upper (i = 1) to lower (i = 2) limb, from the proximal to the distal parts, joints, and the hand or walking, however, the software module allows the separate assessment (Fig. 4).

3. The motor functions assessment. The both limbs are divided into proximal (j = 1) and distal departments (j = 2). The assessment of the proximal departments of the upper and lower limbs, which are presented by two joints (k) on each limb: for the upper limb: k = 1 — the shoulder joint, k = 2 — the elbow joint; for the lower limb: k = 1 — the hip joint, k = 2 — knee joint, and the distal departments of upper and lower limbs, which are presented as one joint (k) on each limb: for upper limb: wrist joint; for lower limb: ankle joint, proceeds by three criteria (n = 3): muscle strength, movement volume, muscle tone. The hand (f = 1) is being assessed by three criteria (n = 3), walking (f = 2) is being assessed by one criterion (n = 1) (Fig. 4).

The interface contains tools for selecting the motor functions assessment of upper or lower limb's joints, hand or walking by relevant criteria. The windows that present descriptions of these criteria are opened using these tools, and the operator selects the necessary assessment option. If there is no selection, the program stops. The calculation of the paresis degree according to Table 3 is performed using data from the buffer on the state of the patient's motor functions in grades, which are entered by the operator in the buffer (Fig. 4). The calculation data is also stored in the buffer.

From the buffer, the results of test are displayed on the screen, where all the information on the motor functions is illustrated both by single criteria and by the total quantitative assessment of relevant joints of limbs, hand or form of walking is illustrated.

The operator can review the results after each assessing stage of assessment and decide whether enough data has already been obtained or continue working without reviewing the data. And the operator proceeds to additional assessment of limbs' motor functions at the level of the joints, hands or passages in case of insufficient data (Fig. 4).

In case of making the decision on a sufficient amount of data the operator stores them together with general patient's information in electronic medical record (EMR). A session with this patient ends (the program goes to the initial state) or the operator exits the program (Fig. 4).

The storing of motor functions testing data in electronic medical record enables one to quantify the rehabilitation effectiveness by testing at the beginning and at the end of rehabilitation course, to study the dynamics of motor functions deficit by three or more testing in one course for prediction and secondary prevention of muscle disorders, to compare the effectiveness at different stages of rehabilitation.

## CONCLUSIONS

The structural and functional model of the program module for personal diagnosing of motor functions in patients after stroke and the efficiency of motor functions restoring as a result of rehabilitation measures has been developed. An algorithm for diagnosing the motor function disorder degree of the affected limbs in patients after stroke and activity diagram of the software module in the UML notation are presented.

The software module "Movement Test Stroke" has been made in Visual Studio 2013 software environment, the programming language is C#. The functional interaction of its components has been developed and described using Unified Modeling Language (UML). It is installed in the PC structure.

Diagnostic benefits: the ability to obtain an integral quantitative assessment of the motor functions deficit of separate joints of the upper or lower limb (by two criteria), hand (by three criteria) and walking (by one criterion) at different stages of rehabilitation, as well as a separate assessment of muscle hyper- or hypotone. It allows carrying out a detailed analysis of the motor function deficit dynamics during rehabilitation measures, to identify the specificity of disorders, to conduct a comparative assessment of individual indicators of rehabilitation efficiency.

The benefit of diagnosing is also that the assessment of motor functions disorder degree of the affected limbs is performed relative to the patient's own healthy limbs, the motor functions of which characterize the individual norm of disorders absence.

Equal six-step gradation of paresis degree, unsurpassed quantitative characteristics of motor functions rehabilitation efficiency linked to generally accepted verbal assessment of effectiveness (unchanged, minor improvements, improvements, major improvements) reduce the expert error.

The quantitative assessment of motor function deficit by evidential criteria, which is provided by the software module “Movement Test Stroke”, is the basis to synthesize the digital health mobile means for information and advisory assistance to the physician in creating and making adjustments to personal plan for recovery the motor functions affected by pathology at different stages of stroke rehabilitation.

The software module "Movement Test Stroke" can be used for motor functions diagnostics not only after stroke, but also for traumatic brain injuries, brain tumors etc.

The program module enables one to evaluate the rehabilitation effectiveness and to study the dynamics of motor functions deficit for the prediction and secondary prevention of muscle disorders during course, and to compare the rehabilitation effectiveness on its different stages.

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# ПРОГРАМНИЙ МОДУЛЬ ПЕРСОНАЛЬНОЇ ДІАГНОСТИКИ РУХОВИХ ФУНКЦІЙ ПІСЛЯ ІНСУЛЬТУ

**Вступ.** Діагностика рухових функцій після інсульту відіграє важливу роль у формуванні реабілітаційної програми. Результати попередньої клінічної апробації запропонованої нами методики кількісного оцінювання дефіциту рухових функцій у ході досліджень динаміки відновлення рухів на базі біоінформаційної технології керування рухами ТРЕНАР® підтвердили доцільність використання цієї методики для створення нових алгоритмічних і програмних засобів персонального діагностування рухових функцій.

**Мета статті** — розробити спеціалізований модуль персонального діагностування рухових функцій у хворих після інсульту, який програмно реалізує визначення ступеня порушень рухових функцій і результатів їхнього відновлення за новою методикою персонального кількісного оцінювання дефіциту рухових функцій.

**Результати.** Розроблено структурно-функціональну модель програмного модуля персональної діагностики рухових функцій і ефективності їхнього відновлення внаслідок реабілітаційних заходів у хворих після інсульту.

Надано алгоритм діагностики ступеня порушень рухових функцій уражених кінцівок у пацієнтів після інсульту і діаграму діяльності програмного модуля у нотації UML.

Програмний модуль "Movement Test Stroke" виконано у програмному середовищі Visual Studio 2013, мова програмування C#. Функціональну взаємодію компонентів модуля розроблено та описано із застосуванням уніфікованої мови моделювання (UML). Модуль встановлено у структурі ПК.

Переваги діагностування: можливість отримувати інтегральну кількісну оцінку дефіциту рухових функцій верхньої та нижньої кінцівок на рівні окремих суглобів, кисті та ходи за відповідними доказовими критеріями, а також оцінку гіпер- або гіпотонусу м'язів на різних етапах реабілітації. Перевагою діагностування є й те, що оцінювання ступеня порушень рухових функцій уражених кінцівок проводиться відносно власних здорових кінцівок пацієнта, рухові функції яких характеризують індивідуальну норму відсутності порушень.

**Висновки.** Кількісна оцінка дефіциту рухових функцій за доказовими критеріями, яку надає програмний модуль "Movement Test Stroke", є основою синтезу мобільних засобів цифрової медицини інформаційно-консультативної допомоги лікарю у формуванні та внесенні корективів до індивідуального плану відновлення пошкоджених патологією рухових функцій на різних етапах реабілітації.

***Ключові слова**: програмний модуль, структурно-функціональна модель, діагностика, алгоритм, рухові функції, персональна кількісна оцінка, інсульт.*

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## ПРОГРАММНЫЙ МОДУЛЬ ПЕРСОНАЛЬНОЙ ДИАГНОСТИКИ ДВИГАТЕЛЬНЫХ ФУНКЦИЙ ПОСЛЕ ИНСУЛЬТА

**Введение.** Диагностика двигательных функций после инсульта играет важную роль при формировании реабилитационной программы. Результаты предварительной клинической апробации предложенной нами методики количественной оценки дефицита двигательных функций при исследовании динамики восстановления движений на базе биоинформационной технологии управления движениями ТРЕНАР® подтвердили целесообразность использования этой методики для создания новых алгоритмических и программных средств персонального диагностирования двигательных функций.

**Цель статьи** — разработать специализированный модуль персонального диагностирования двигательных функций у больных после инсульта, который программно реализует определение степени нарушений двигательных функций и результатов их восстановления по новой методике персональной количественной оценки дефицита двигательных функций.

**Результаты.** Разработана структурно-функциональная модель программного модуля персональной диагностики двигательных функций и эффективности их восстановления в результате реабилитационных мероприятий у больных после инсульта. Представлены алгоритм диагностики степени нарушений двигательных функций пораженных конечностей у пациентов после инсульта и диаграмма деятельности программного модуля в нотации UML.

Программный модуль "Movement Test Stroke" выполнен в программной среде Visual Studio 2013, язык программирования C#. Функциональное взаимодействие компонентов модуля разработано и описано с использованием унифицированного языка моделирования (UML). Модуль установлен в структуре ПК.

Преимущества диагностики: возможность получать интегральную количественную оценку дефицита двигательных функций верхней и нижней конечности на уровне отдельных суставов, кисти или ходьбы по соответствующим критериям, а также оценку гипер/гипотонуса мышц на различных этапах реабилитации. Преимуществом диагностирования является и то, что оценка степени нарушений двигательных функций пораженных конечностей проводится относительно собственных здоровых конечностей пациента, двигательные функции которых характеризуют индивидуальную норму отсутствия нарушений.

**Выводы.** Количественная оценка дефицита двигательных функций, которую обеспечивает программный модуль "Movement Test Stroke", является основой синтеза мобильных средств цифровой медицины информационно-консультативной помощи врачу в формировании и внесении коррективов в индивидуальный план восстановления поврежденных патологией двигательных функций на разных этапах реабилитации.

***Ключевые слова***: *программный модуль, структурно-функциональная модель, диагностика, алгоритм, двигательные функции, персональная количественная оценка, инсульт.*

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# TRANSFORMATION OF CLINICAL DECISION SUPPORT SYSTEMS INTO FHIR STRUCTURES TO ENSURE QUALITY OF MEDICAL CARE

***Introduction.*** *The reform of the medical sector in Ukraine has given impetus to the development of eHealth and, as a consequence, the creation of medical registers systems and specialized medical information systems to support the operation of primary health care etc. One of the strategic directions of the health care system is to find and choose effective methods of managing the quality of care.*

***The purpose of the paper*** *is to analyze the conditions and opportunities for transformation of the clinical decision support system using standard Fast Healthcare Interoperability Resources (FHIR) structures to ensure health care quality control.*

***Results.*** *The current level of medical information systems development requires the application of the international standard FHIR, which are applied for the exchange of data between different systems of electronic medical records and between different components of the same electronic medical record (EMR) system, for standardization of interoperability.*

*Uninterrupted improvement model, known as the Plan-Do-Check-Act (PDCA), which consists of four components — planning, executing, testing and improving own process, is considered. The characteristics of the FHIR standard are analyzed and ways of transforming the clinical decision support system based on this standard are identified. The concept of an abstract data node, ensuring terminological compliance, implementation of the Workflow data model, and other functions and tasks of the clinical decision support system are described.*

***Conclusions.*** *One of the important areas of eHealth development is to implement the information systems forcare quality managing based on modern information medical standards. Creation and implementation of effective methods for monitoring (identifying) diagnostic and treatment quality* *in hospital will foster optimization and increase of their activity efficiency.*

*The use of the FHIR framework in the creation of information support system for evaluating the care quality enables to improve the data exchange quality and their processing for decision-making.*

***Keywords:*** *eHealth, FHIR structures, clinical decision support system, health care quality control.*

## INTRODUCTION

The digital transformation of society has also touched such an important area as healthcare. Against this background, digital medicine, covering virtually all areas of the health care system has emerged.

The reform of the medical sector in Ukraine has given impetus to the development of eHealth and, as a consequence, the creation of medical registers systems and specialized medical information systems to support the operation of primary health care etc.

One of the strategic directions of the health care system is to find and choose effective methods of managing the quality of care. National programs for improving quality of health care have been developed in a number of countries based on the use of information standards to solving these problems. Let us mention the Veterans Health Administration (VHA) program of the Quality Study (QUERI), which aim sat ensuring excellence in all areas where the VHA provides medical services, including inpatient, outpatient and long-term care. Significant emphasis is placed on the role of information systems in the health care quality estimation [1]. An analysis of published studies on the PubMed, Scopus, Cochrane Library, and other databases has shown a significant impact of the electronic medical records (EMR) use on health care quality, primarily reducing the time on documentation [2].

According to WHO definition, the most important criteria for quality of care are the degree of reduction of the risk of possible disease, progression of the existing disease, the development of complications due to the disease, examination and treatment, taking into account the optimal use of available medical resources and technologies, as well as the patient's satisfaction with the medical care [3–7]. The importance of making evidence-based decisions resulting from monitoring and in-depth analysis of information which comes from using a variety of software is essential for the implementation of guarantees and the quality of care. However, so far, there is no general position in the Ukrainian healthcare facilities on implementing the continuous quality improvement concept. Mechanisms of ensuring a guaranteed level of care quality are underway. Elements of information infrastructure are being created for the medicine needs, the beginning of development, application and spreading modern information means for health care has been done [8]. However, developed information systems tend to be narrowly focused on supporting separate functions and tasks, there is no unified approach to these systems development for united information medical environment [9, 10].

The topicality of this problem is due to its extreme importance for one of the most expensive and resource-intensive types of medical care — inpatient care. Creation and implementation of effective methods for monitoring quality of the diagnosis and treatment in hospitals will allow to optimize and increase their efficiency.

Therefore, one of the important areas of eHealth development is to implement the information systems for care quality managing based on modern information medical standards.

## PROBLEM STATMENT

Healthcare information technology (IT) tools that support the assessment of medical care quality (QI) allow us to measure, track, analyze the effectiveness of medical care and monitor the improvement of clinical process, influence on the overall patients` health and the coordination of medical care, the attempt to reduce costs and improve the health of the patient. Such tools are based on EMRs with structured data. These structured EMRs can be used to collect baseline data and to analyze, report and track data [11].

The use of EMRs is the basis for the development of various information resources. Registries (e.g., for specific diseases, immunizations, prevention and procedures) help to identify care gaps for the maximum benefit for patient and for improving the organization of such care. For the most effective work, registries must be interconnected and integrated into the workflows of practical medicine. Electronic medical records accumulate data of laboratory results, vaccination, medication use, and other patient care information. This information may be provided to other healthcare facilities and medical professionals to coordinate care for different patients.

Decision support systems based on effective digital medicine techniques for EMF analysis are capable of improving the health care quality. Clinical Decision Support System (CDSS) is an independent set of medical information system (MIS) components focused on information support for clinical and economic decision making. Such systems implementation has already shown their importance in managing the treatment process quality and in providing evidence for medical recommendations [12–15].

Today, all information systems have to meet certain standards of the exchange of information and data, the electronic records format, the information protection etc. One of the most common standards for the exchange of medical data and information is the Health Level 7 standard (HL7), a number of its versions also regulate electronic medical records formats [16].

The current level of medical information systems development requires the application of the international standard FHIR, which are applied for the exchange of data between different systems of electronic medical records and between different components of the same EMR system, for standardization of interoperability, as well as for the implementation of the functional model EMR [17].

The FHIR standard is a development of the HL7 standard, the changes in the set, new extensions, and a formal profile added to the first previous versions of FHIR to express basic minimum metadata. In 2014, the first draft of the standard for trial use (DSTU1 0.0.82) was issued. “DSTU Version 2 QA Preview, Aug 31 2015” had major changes regarding transaction integrity, URL resolution rules were changed, new and altered data types, new and changed internal resources (regarding patient records, reviews, and techniques, diagnosis and treatment plans, etc.) were specified. Then, for several years, work was done to improve the new standard, using the experience of its implementation in practical medicine. The FHIR R4 version has been in force since December 2018, with many significant changes compared with the first regulatory content [18].

The main FHIR elements are the modular components — Resources. By analogy with “the set of blocks”, these Resources build specific systems that meet the requirements of the healthcare facility and provide easier solutions to current clinical and administrative issues. FHIR is suitable for use in a wide variety of contexts — applications for mobile phones, cloud communications, EMR-based data sharing, server communication with major healthcare facilities, and more [19, 20].

One of the FHIR implementations is the OncoWorkStation (OWS) Chemotherapy Planning System, which implements a PlanDefinition as block diagram for the choice of treatment regimen and implementation of the Order Set with the generation of a highly differentiated personal CarePlan for chemotherapy worksheet [3, 4]. The system has been used effectively for several years and with adaptation to the specifics of various German clinics in adult and pediatric practice. OWS chemotherapy plans include about 100–150 treatment regimens in adult oncology and 24–28 (98 % of all available) regimens in pediatrics. OWS plans implemented a section of medication prescriptions permitted at the time of implementation of the clinical protocols. They consisted of flowcharts of treatment regimens and direct sets of orders that generated CarePlan. The “Event-Condition-Action” rules (ECA) were overwhelmingly concerned with changes in chemotherapy doses or medications depending on laboratory or patient data.

In OWS, the rules were stored not as a program code, but as a database node as part of an action plan. This database structure was read and interpreted as rules.OWS automated verification has not been considered or implemented. Improvement of this system was carried out according to the results of its practical use.

Summarizing, clinical practice processes and their organization consist of structured procedures for measuring and reporting results at the health facility and at the physician level. Improving these processes and adapting to daily practice is based on evaluating the health care quality that activates feedback to improve patient care. The use of FHIRs will increase the efficiency of data exchange between all participants in the healthcare process.

**The purpose of the paper** is to analyze the conditions and opportunities for transformation of the clinical decision support system using FHIR structures to ensure health care quality control.

## MODEL OF UNITERRUPTED IMPROVEMENT AS THE BASIS OF IMPROVING THE TREATMENT AND DIAGNOSIS QUALITY

The quality of the diagnostic and treatment processes, like any other process, is achieved by the cyclic application of a uninterrupted improvement model, known as the Plan-Do-Check-Act (PDCA), which consists of four components — planning, executing, testing and improving own process [21].

According to the requirements of the IT industry development, the treating process reflection is carried out by the business process flows method.

Creating high-quality workflows is a cyclical process of their formal description, integration of these workflows during medical documentation in hospital, gathering information on the implemented measures effectiveness, using information needed to improve them, their updating on the basis of collected world and own data.

The medical-diagnostic process description, from the FHIR, is the sequence of EMRs on completion of each of its components, recording of the medical condition (Condition), of the examinations, analyzes (Observation), appointments (CarePlan) in the format described in the Clinical Module FHIR. Electronic medical record is the main component of MIS, on the basis of which all other modules of treatment quality providing are built. The FHIR architectural framework provides data models and recommendations for the implementation of each of these parts.

**Treatment planning**. The expertise and experience of the treating physician are the key component of the care quality. Modern MIS uses the implementation of the FHIR specification to define and execute an action plan (AP) for organizing and managing workflows, enables the physician or group of physicians to present their expertise of the treating process in the form of computerized action plans. These plans are the first and the main component of quality assurance, according to the Deming cycle.

Meta-Content-Relational Database Model (MCR-DB) was developed on the basis of relational database, using five types of constraints for the primary and secondary key of the abstract data node, for implementing all the necessary FHIR structures, achieving NoSQL database functionality and solving other tasks of the healthcare institution.

The Workflow FHIR module and the Clinical Reasoning module of the FHIR framework describe data models and modes that allow them to formally express physician knowledge, interactively use it to guide the treating process, and make it possible to evaluate and improve them. The workflow in FHIR is defined in a declarative programming paradigm in which the structures and elements of a computer program express the calculation logic without describing the sequence of its execution.

Workflow is an algorithm defined in the format of a separate structure – Plan Definition, as a set of tasks (Task) to collect and analyze the data needed to make the right clinical decision, as well as documenting the actions to ensure the treatment process, in accordance with the level of knowledge at the time of their creation. The peculiarity of these algorithms is that they are executed interactively - partly programmatically, partly by person.

The tasks are grouped into blocks that are the workflow process nodes at the same time and in the same logical space.

Formalized action plans are divided into different types, usually by their field of use. Simple Action Plans are: organizational communication (Order Set of Surveys or Assignments), status assessment (ECA rule sets), etc. Comprehensive action plans are the patient routes, computerized clinical protocols. Different types of action plans are often combined.

**The implementation** of computerized **plans** for medical treatment is interactive. Software implementation of the action plan is prescribed in the paradigm of event-oriented programming by determining the event template (Event Definition, Event) and the user, in the form of a trigger (Trigger Definition) to track the event. Event templates prescribe ECA rules for interpreting certain electronic medical records or their groups as requiring activity events. Events can be defined as separate system elements or specific components of some action plans.

The AP tasks fulfillment after their activation is carried out in stages preserving the statuses of fulfillment (Workflow State): "in process", "request is made", "answer is sent", "accepted", "rejected"; "completed", "failed", "canceled".

To formulate action plans, tasks are defined in such a way that, as a result of their fulfillment, they are stored in the corresponding medical documents (Documents) as electronic medical records of the specified coding systems.

Action plans can be implemented either directly sequentially for the implementation of the treatment process or indirectly, for comparison with existing electronic medical records and plans, as well as for finding unfulfilled or unconfirmed items of tasks.

**The validation** of the treatment process consists of two parts: control of the correctness of the action plans execution by audit (Audit Event) and the collection of information needed to improve the action plans according to pre-planned data collection in FHIR format (Measure). Measurements and audits can be applied to any AP element: tasks, rules, assignments, etc.

**Improving** the treating process is a scientifically founded, guided creative process for improving action plans. This process is based on the collected personal and world information (knowledge) of evidence-based medicine. Improvement of existing action plans is provided by the proper organization and use of internal clinical audit.

Improvements to the plans themselves are achieved using the Deming PDCA approach, which enables purposeful measurements of results and their statistical processing by various methods: data stratification, finding the data significance (Pareto diagram) and cause and effect relationships (Ishikawa diagrams) or comparison of world evidence-based medicine.

## CHARACTERISTICS AND POSSIBILITIES OF THE FHIR STANDARD APPLICATION IN THE CLINICAL DECISION SUPPORTING SYSTEM

**FHIR approach to CDSS implementation and clinical quality framework.** As noted, quality management is implemented using an EMR by maintaining links with relevant additional data structures. The EMR Task Plans link shows which CDSS programs were used for this purpose.

The Clinical Quality Framework adds the opportunity to extend the relevant Measure tasks to test the effectiveness of the use of particular clinical recommendations or to collect data for improving them.

Recoverable Data linking combines the essence, activities, and agents underlying CDSS debugging and clinical auditing, forms the evaluation basis for authentication, on the semantic network (W3C PROV).

The CDSS tasks complexity and clinical quality frameworks require an internal scripting language to navigate data structures such as XPath and Clinical Quality Language (CQL).

Knowledge presentation is a component that provides perceptions and interoperability of formally described action plans, event-state-action rules system, order sets (evidence-based clinical checklists, clinical protocols), and are an integral part of the CDSS user interface.

**Implementation of the FHIR approach to the clinical decision support system.** To implement the described requirements of MIS, it is necessary to create a database, which, in addition to preserving EMR function, must ensure that the body of the program and the trace for its fulfillment are stored in the DB nodes. To do this, we suggest using a meta-content-relational database model.

The program body preservation is interpreted during their analysis, such as s-expressions, in LISP-style, that makes it possible to define both data and procedures. The trace of such programs execution is stored not in RAM, but in the database for further verification.

Data trace statistical analysis gives an opportunity to evaluate the use frequency and its authenticity (clinical audit) as well as to process the measurements for proving the treatment effectiveness, as well as identifying new treatment quality indicators to further improve the program action plans.

The application of the three components of the relational database configuration capability enables the creation of a meta-content-relational database model based on the relational database as the necessity for the specified requirements implementation.

It is appropriate to investigate the ability of using FHIR for implementing the Clinical Query Language requirements. MCR-DB uses one single primary key (id) for all database tables.

**The concept of abstract data node.** The prerequisite for the proposed model implementation is the use of a single primary key for all database tables.

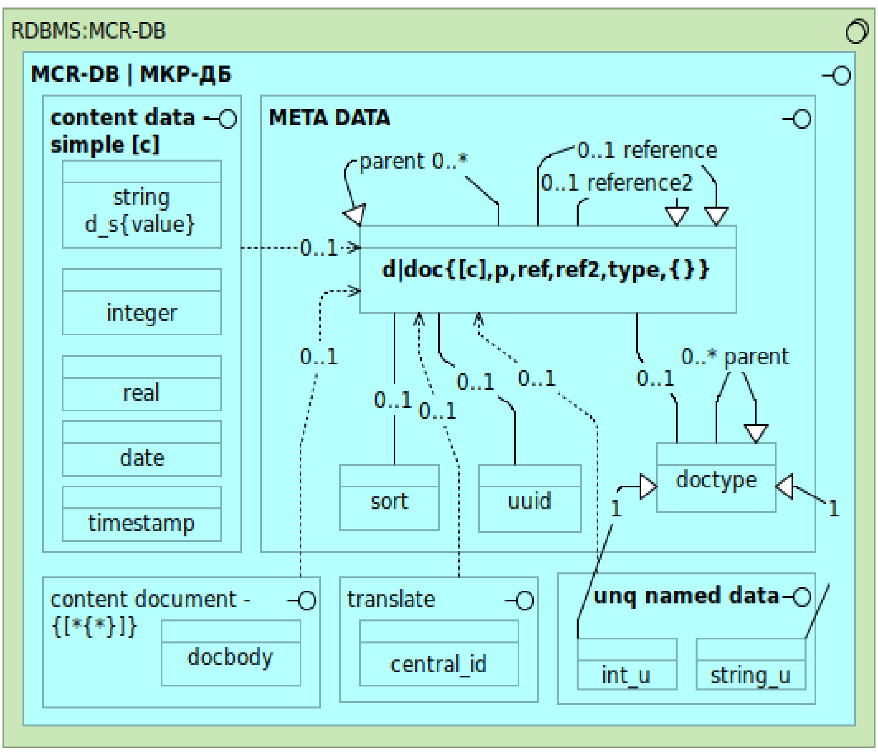


*Fig. 1:* Meta-content-relational database model

The concept of an abstract data node is introduced:

ADN|АВД □ doc {[c], p, ref, ref2, type, {}} alias doc|d is a **META DATA** group.

The sequence of keys inside {} is selected according to the frequency of use to be kept, as in case of the use of () to call functions.

Note the properties of the keys. Linking AVD 0..n to content [c] is by using the first key of the link d.id :[c.id] with tables with one simple type field — **content data group - simple[c]**.

The *second key* that organizes tree structure of the parent|p :doc.id 0..* data is the most commonly used, *third* and *fourth keys* with reference to other nodes (0..1 reference|ref|r :doc.id, 0..1 reference2|ref2|r2 :doc.id) are used if intended. The AVD class is defined by the doc link table, which is one for the entire database, and has three secondary keys. The AVD object is implemented by listing the data in one row of the link table.

In describing a hierarchical data structure, it is possible to use an attachment as the second parameter, for example d{,d{}} will mean a structure with a second level hierarchy. It is possible to use the numbers d{,3d{}} to abbreviate the depth of attachment or d{,3-5d{}} to describe the depth range.

Generally, the third parameter (ref) is used to refer to a data type, for example, FHIR, and the fourth parameter (ref2) is to refer to dictionary data.

An additional AVD parameter provides data typing by linking to a data type table (*fifth key*) that has its own hierarchical links of parent nodes. The type parameter defines simple node data or object {} for complex data types. A parameter of type [] denotes a data array. Re-defining simple types with an array|[]|| [].* reference indicates that this AVD is a data array of the appropriate type. A hierarchical combination of AVD nodes of types {} and [] provides the ability to generate arbitrary complexity JSON document in MCR-DB model.

The supplemental content table, "docbody", can store the various software structures needed to accelerate the FHIR work and implementation: a JSON document (which has a data structure generated elsewhere in the MCR-DB), SQL templates (data selection procedures for executing expressions and action plan procedures), HTML blocks (for submitting data and for constructing the user interface according to their content).

**Ensuring terminological compliance**. The correspondence of ICD-10 vocabularies and the FHIR terminology module is implemented by means of the defined connections of these two systems (Fig. 2):

ICD10 — md.ICD10 | d {, d {, 3-5d {[su, iu]}}}
ICPC2 — md.ICPC2 | d {, d {, d {[su, iu]}}}
ICD10 links with ICPC2:
- md.ICD10_ICPC2 | d{, p:d.id, ref:md.ICD10, ref2:md.ICPC2}

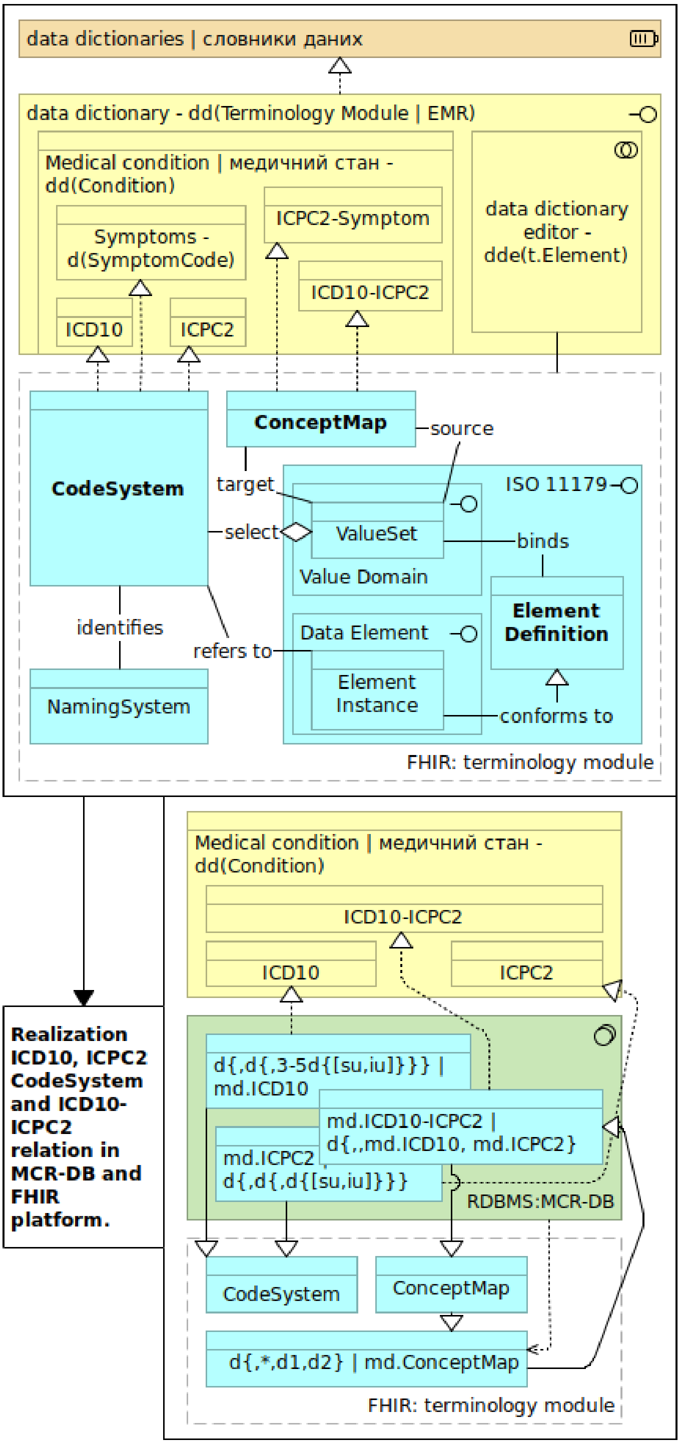


***Fig. 2.*** Use of FHIR terminology module and implementation of MKH-10 classifiers (ICD10, ICPC2) and ICD10-ICPC2 ratios in MCR-DB and FHIR platform

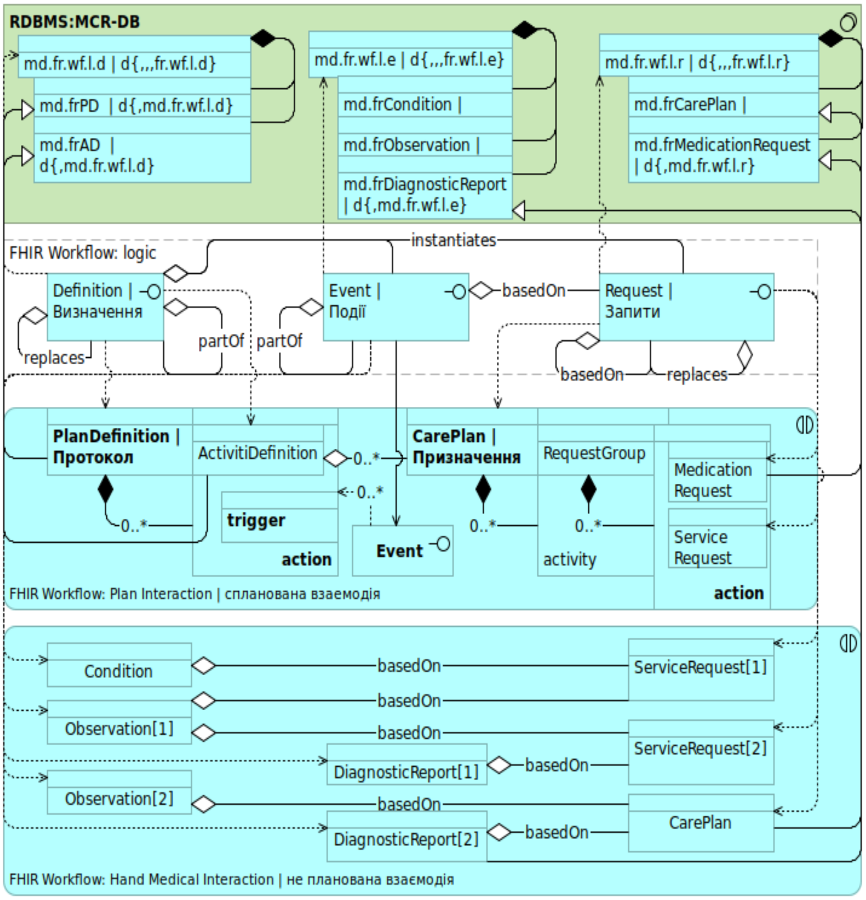


***Fig. 3.*** FHIR: Workflow — RDBMS: MCR-DB

This procedure is organized using the FHIR ConceptMap metadata implemented by the MCR-DB pseudo-expression ADN□md.ConceptMap | d {, *, ref: d1.id, ref2: d2.id:}.

**Implementation of the Workflow data modelin nMCR-DB pseudo-expressions** (Fig. 3). The logic of Workflow in FHIR is embedded and described in three corresponding logical structures: Definition, Request and Event. These structures have properties similar to the interface in Java object-oriented programming. Using nMCR-DB, we can classify them as metadata by means of the following statements:

ADN.type□fr.wf.l. * | FHIR.Workflow.logic. *;
ADN □ d {,,, type: fr.wfl.d} | md.fr.wf.l.d | FHIR.Definition;
ADN □ d {,,, type: fr.wfl.r} | md.fr.wf.l.r | FHIR.Request;
ADN □ d {,,, type: fr.wfl.e} | md.fr.wf.l.e | FHIR.Event;

At the same time, the following classes are indicated accordingly the following statements:

md.frPlanDefinition | md.frPD | d {,,, fr.wf.l.d};
md.frActivitiDefinition | md.frAD | d {,,, fr.wf.l.d}.

The FHIR Framework's Workflow recommendations apply event-oriented programming approaches and software design pattern principles. In the FHIR Workflow: Plan Interaction ( Fig. 3) shows part of the pattern, by which implementing an event-oriented programming approach is suggested to organize the treating process support.

## THE UNITY OF FHIR ORGANIZATIONAL APPROACHES AND CLINICAL DECISION SUPPORT SYSTEMS FOR IMPROVING THE HEALTH CARE QUALITY

The CDSS-FHIR approach practically provides a model software framework that is generally consistent with the quality management model of the decision support system for improving the care quality.

The generalized strategy is inherently the PDCA Demur model taking into account motivational aspects (Fig. 4). The planning function corresponds with the clinical guidelines implemented in the format of the FHIR PlanDefinition.

In the two approaches under consideration, the use of the audit and the connection with the official medical documents are almost identical.

In the implementation of these methods, during the construction of the relevant information system, the data gathering functions were defined for different information: concerning the course of the disease and the results of the main and auxiliary treatment processes, processing, analysis, transfer of the received information for use in decision-making at different levels of assessment management of care quality and effectiveness.

Thus, the system is intended for use by treating physicians, heads of clinical departments according to the distribution of functional responsibilities, as well as non-clinical unit managers and their staff involved in the supportive processes.

Peculiarities of the systems` organizational structure are deep involvement of staff in quality management, that is why the system is distinguished: the first level of management - executors (self-management), the second level - heads of departments and heads of structural units, the third level - hospital management. In addition, the quality management system includes a number of matrix control structures. The object of management is the complex of processes, i.e. basic (medical care) and ancillary (security and organizational) processes.

The functioning of the system is ensured by the information flow between the participants of the control process in both directions. The information is the result of the collection, evaluation and analysis of data concerning the course of the disease, as well as the effectiveness and efficiency of treating processes. This information is internal, that is, information from one's own sources. External information includes policy and scientific information as well as information on the medical audits results.

All types of information and means for its automated collection, processing and analysis for later use at any level of control of any matrix structure are reflected in the control unit.

Information from one's own sources is formed on the basis of data about events at the processes "key points" and points of their interaction with each other and with the external environment. It is the information that is important for evaluating the effectiveness and efficiency of health care delivery processes.

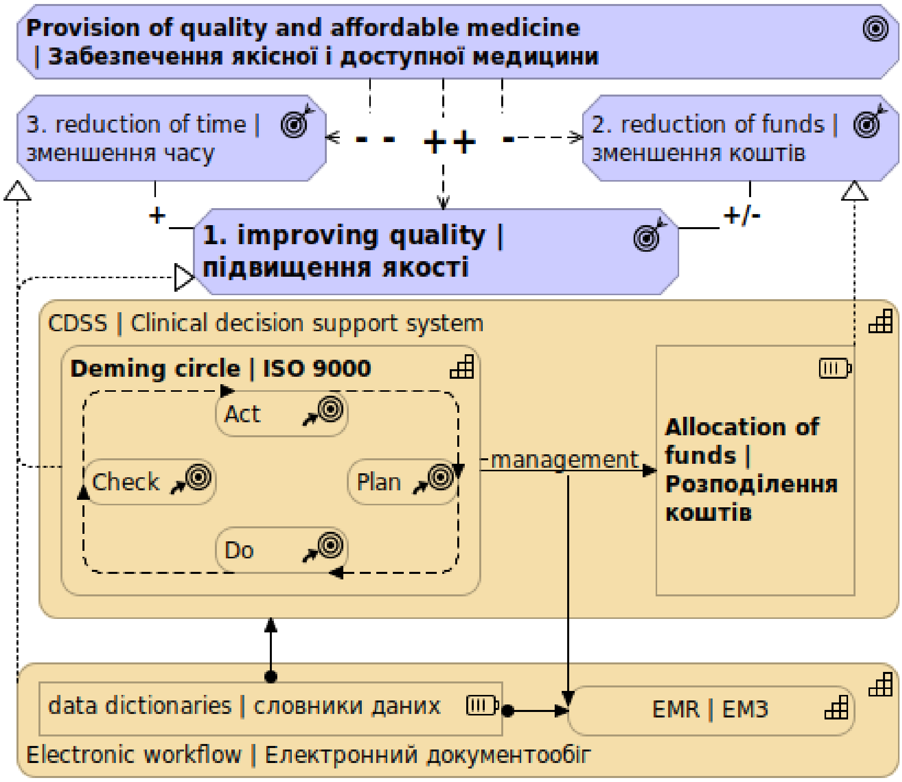


***Fig. 4.*** The generalized strategy for improving the health care quality

As sources of information are as follows: "Medical card of inpatient patient" (f. № 003/o), filled according to the requirements, including information about the result of treatment (recovery, clinical condition improvement, clinical condition without changes, worsening of clinical status, compensation of chronic disease exacerbation, chronic disease subcompensation, fatal consequences), "Statistical card of the patient who left the hospital" (f. № 066/o), filled in according to the requirements, "Extract from the medical card of the inpatient patient" (f. № 027/o), "Procedure Log" with the patient's identification, "Diagnostic and Treatment Card" according to the established quality indicators.

In health care facilities where clinical decision support systems are planned, regulations of local level processes should be worked out and implemented in accordance with the established requirements: clinical protocols of medical care, drug lists, clinical routes of patients, technical standards for governing the main and ancillary processes.

The local clinical care protocol is a document that defines the requirements for diagnostic, treatment, prophylactic and rehabilitation measures, their interrelation and the sequence of implementation in a clinical facility. The local clinical protocol allows physicians to apply the most clinically and cost-effective medicines with the lowest side effects risk. The clinical route of the patient is an organizational component of the health care providing.

The criteria for the care quality assessing are not only reference point for data collection, but are also used as a guide for further evaluating the performance level of the relevant process. These criteria are divided into organizational and technological. Organizational criteria make it possible to evaluate the degree of compliance with organizational standards, and technological ones — with clinical regulations.

Therefore, clinical decision support systems are based on the knowledge of the means of support and correction of patients' health, accumulate the results of observations of changes in health state under different conditions, and make it possible to evaluate the care delivery quality for the further improvement the health care personnel. CDSSs are regarded as active knowledge systems that allow using a range of professional expertise to generate specific medical suggestions for diagnostic and treatment processes.

## CONCLUSIONS

One of the important areas of eHealth development is to implement the information systems for care quality managing based on modern information medical standards. Creation and implementation of effective methods for identifying diagnostic and monitoring treatment quality in hospital will foster optimization and increase of their activity efficiency.

The use of the FHIR framework in the creation of information support system for evaluating the care delivery quality enables to improve the data exchange quality and their processing for decision-making.

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## ПЕРЕХІД СИСТЕМ ПІДТРИМКИ ПРИЙНЯТТЯ КЛІНІЧНИХ РІШЕНЬ В FHIR СТРУКТУРИ ДЛЯ ЗАБЕЗПЕЧЕННЯ ЯКОСТІ МЕДИЧНОЇ ДОПОМОГИ

**Вступ.** Реформа медичної галузі в Україні зробила поштовх до розвитку електронної охорони здоров’я і, як наслідок, створення системи медичних реєстрів та спеціалізованих медичних інформаційних систем підтримки функціонування первинної медичної допомоги тощо. Одним зі стратегічних напрямків системи охорони здоров'я є пошук і вибір ефективних методів керування якістю медичної допомоги.

**Мета статті** — аналіз умов та можливостей трансформації системи підтримки прийняття клінічних рішень з використанням структур інформаційної швидкодії Fast Healthcare Interoperability Resources (FHIR) для забезпечення контролю якості медичної допомоги.

**Результати.** Сучасний рівень розроблення медичних інформаційних систем зумовлює застосування міжнародного стандарту FHIR — ресурс швидкої взаємодії в галузі охорони здоров'я, який використовується для обміну даними як між різними системами електронних медичних записів, так і між різними компонентами однієї ЕМЗ-системи, для стандартизації інтероперабельності. Розглянуто модель безперервного поліпшення якості процесу, відомої як цикл Демінга (Plan-Do-Check-Act (PDCA)), який складається з чотирьох складників — **планування**, **виконання**, **перевірки** і **вдосконалення** цього процесу.

Проаналізовано характеристики стандарту FHIR та визначено шляхи трансформації системи підтримки прийняття клінічних рішень на основі цього стандарту. Описано Поняття абстрактного вузла даних, Забезпечення термінологічної відповідності, Імплементацію моделі даних Workflow та інші функції та завдання системи підтримки прийняття клінічних рішень.

**Висновки.** Одним із важливих напрямів розвитку eHealth є впровадження інформаційних систем керування якістю надання медичної допомоги на основі сучасних інформаційних медичних стандартів. Створення та впровадження ефективних методів моніторингу (виявлення) якості діагностики та лікування сприятиме оптимізації та підвищенню ефективності діяльності закладів охорони здоров’я. Використання стандарту FHIR у створенні системи інформаційної підтримки для оцінювання якості надання послуг дає змогу покращити якість обміну даними та їхнє оброблення для прийняття рішень.

***Ключові слова*:** eHealth, структури FHIR, система підтримки прийняття клінічних рішень, контроль якості охорони здоров'я.

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## ТРАНСФОРМАЦИЯ СИСТЕМ ПОДДЕРЖКИ ПРИНЯТИЯ КЛИНИЧЕСКИХ РЕШЕНИЙ В FHIR СТРУКТУРЫ ДЛЯ ОБЕСПЕЧЕНИЯ КАЧЕСТВА МЕДИЦИНСКОЙ ПОМОЩИ

Современный уровень разработки медицинских информационных систем обуславливает применение международного стандарта Fast Healthcare Interoperability Resources (FHIR) — ресурс быстрого взаимодействия в области здравоохранения, который используется для обмена данными как между различными системами электронных медицинских записей, так и между различными компонентами одной системы для стандартизации интероперабельности. Рассмотрена модель непрерывного улучшения качества процесса, известная как цикл Деминга (Plan-Do-Check-Act (PDCA)), который состоит из четырех частей — планирование, исполнение, проверка и совершенствование этого процесса.Проанализированы характеристики стандарта FHIR и определены пути трансформации системы поддержки принятия клинических решений на основе этого стандарта. Описаны понятие абстрактного узла данных, обеспечение терминологического соответствия, имплементация модели данных Workflow и другие функции и задачи системы поддержки принятия клинических решений.

***Ключевые слова***: *электронное здравоохранение, структуры FHIR, система поддержки принятия клинических решений, контроль качества здравоохранения.*

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# ДО УВАГИ АВТОРІВ!

У журналі надано результати досліджень в галузі теорії і практики інтелектуального керування, інформатики та інформаційних технологій, а також біологічної і медичної кібернетики.
Цільова аудиторія — науковці, інженери, аспіранти і студенти вищих навчальних закладів відповідного фаху.

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1. Рукопис надають на папері у двох примірниках (мова – англійська, українська, російська, 17–22 с.) та електронна версія. До рукопису додають:

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## Вимоги до текстового файлу

Формат файлу * .doc, * .rtf. Файл повинен бути підготовлений за допомоги текстового редактора Microsoft Word.

Використовувані стилі: шрифт Times New Roman, 12 пт, міжрядковий інтервал — 1,5. Формат паперу А4, всі береги — 2 см.

Формули набирають у редакторі формул Microsoft Equation Editor 3.0. Опції редактора формул — (10,5; 8,5; 7,5; 14; 10). **Ширина формул — до 12 см**.

Рисунки повинні бути якісними, створені вбудованим редактором рисунків Word Picture або іншими Windows-додатками (рисунки надають окремими файлами відповідних форматів). **Ширина рисунків — до 12 см**.

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