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Alexei V. Samsonovich
Valentin V. Klimov
Galina V. Rybina *Editors*

Biologically Inspired Cognitive Architectures (BICA) for Young Scientists

Proceedings of the First International Early Research Career Enhancement School (FIERCES 2016)

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Preface

First School on Biologically Inspired Cognitive Architectures

The emergence of biologically inspired cognitive architectures (*BICA*) *challenges researchers across many disciplines with a new frontier: computational replication of the human mind, taken in all its essential aspects, as a functional unit of a team or a society, based on a biologically inspired approach* (*the BICA Challenge*)*. After many decades of successful progress in the field of artificial intelligence, we understand now that this approach is necessary, because essential qualities of biological intelligent systems like robustness, flexibility, adaptability, communicability and teachability are still unmatched by their artificial counterparts.*

This volume includes papers from the First International Early Research Career Enhancement School on Biologically Inspired Cognitive Architectures: FIERCES on BICA 2016. It is a fierce attack on the challenge, and historically, the first international school on BICA. Its mission is to facilitate interaction and collaboration among top experts in the field (including such names as Christian Lebiere, Frank Ritter, Paul Verschure) and young researchers who devoted themselves to solution of the BICA challenge, by bridging cross-disciplinary, cross-generation, and cross-cultural barriers.

Biologically Inspired Cognitive Architectures (BICA) are computational frameworks for building intelligent agents that are inspired from biological intelligence. Thanks to modern brain imaging and recording techniques allowing us to map brain structures and functions, our present ability to learn from nature how to build intelligent systems has never been greater. At the same time, new techniques developed in computer and cognitive sciences conveniently complement biological inspirations, allowing us to build the software that will unleash the presently available at low cost computational powers to their full extent. Given this situation, an explosion of intelligent applications from driverless vehicles, to augmented reality, to ubiquitous robots, is now almost certain. As a consequence, this first school on BICA is interdisciplinary in nature and promises to yield bidirectional flow of understanding between experts in all involved disciplines.

Topics of articles included in this volume extensively cover the most advanced scientific fields relevant to BICA that are traditionally considered at the international level of significance and discussed at many mainstream national and international conferences on artificial intelligence, neuroscience, and cognitive modeling, including conferences organized by the Russian Association of Artificial Intelligence (RAAI) and by the BICA Society. The list of the latter is quite long. Beginning with the AAAI Fall Symposia on BICA (2008, 2009), the Annual International Conference on BICA has been held every year since 2010, demonstrating progressively growing popularity. Locations of the conference included Arlington, Virginia (near Washington, DC, 2010); Palermo, Italy (2012); Kiev, Ukraine (2013); Cambridge, Massachusets (2014); Lyon, France (2015); and upcoming this year—New York, USA (2016). The present BICA event, however, is unique in its kind.

Specifically, papers included in this volume are a mixture of tutorials and research articles, focused on fundamental and applied areas of cognitive, social and neurosciences and artificial intelligence, including, but not limited, to topics such as cognitive modeling, automated planning and behavior generation, fuzzy models and soft computing, knowledge engineering, ontologies and knowledge management, acquisition, representation and processing of temporal knowledge, applied intelligent systems, dynamic intelligent systems and real-time systems, intelligent tutoring systems, instrumental systems for artificial intelligence. All works included in this volume have been carefully peer-reviewed and refereed, and reflect the high level of ongoing research and development in participating leading universities and research centers around the world, including those in the US, France, Germany, Italy, Spain, Japan, Ukraine, Belarus, and also in Russia (Moscow, St. Petersburg and other Russian cities).

We are grateful to all authors who contributed their works to this volume. We also would like to express our many thanks to all people who helped us with the organization of the first school FIERCES on BICA, primarily including Drs. Aleksandr I. Panov, Olga A. Mishulina, Vladimir G. Redko, Galina A. Beskhlebnova, Ilya Sukonkin, and Ms. Olga N. Petukhova. Last, but not the least, is our appreciation and acknowledgment of the sponsors of FIERCES on BICA. Financial sponsorship was provided by the Russian Science Foundation (Grant No 15-11-30014 to Dr. Alexei V. Samsonovich). Organizational support was provided by Department of Cybernetics of the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute): https://mephi.ru/eng/about/departments/22.php, with the help of BICA Society (http://bicasociety.org).

Moscow, Russia
February 2016

Alexei V. Samsonovich
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The Cognitive Architecture Within the Natural-Constructive Approach

Olga Chernavskaya

Abstract The cognitive architecture designed within the natural-constructive approach to modeling the cognitive process is presented. This approach is based on the dynamical theory of information, the neurophysiology data, and neural computing (using the concept of dynamical formal neuron). It is shown that this architecture enables us to interpret and reproduce peculiar features of the human cognitive process, namely—uncertainty, individuality, intuitive and logical thinking, etc. It is shown that the human emotions could be interpreted as the *derivative* of the noise amplitude, with the absolute value reflects the degree of emotional reaction, while its sign corresponds to negative or positive emotion, respectively; thereby wide spread binary classification gets natural explanation.

Keywords Generation of information · Noise · Image · Symbol · Emotions · Learning

1 Introduction

The problem of comprehension and modeling a cognitive process does attract permanent interest and represents a pronounced example of the inter-disciplinary problem [5, 18, 22]. Indeed, the comprehension of the brain-activity mechanism requires knowledge in physics (as any substantial system), biology (living system), as well as psychology and philosophy (*thinking* and *speaking* system). Recently, new specific direction called "cognitology" has been formed to join both these scientific blocks related to the brain and mind, respectively, with accounting for the "explanatory gap" between them. Within this direction, there are various approaches to modeling a cognitive process (e.g., [16, 20, 23]. In our works [1–3] we have elaborated so called Natural-Constructive Approach (NCA), which is based on the Dynamical Theory of Information (DTI), elaborated in [5, 9], neurophysiology data

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[21], and neural computing [10] combined with the technique of nonlinear dynamic differential equations. This approach is aimed to modeling just the human-level cognition.

It is important to stress that the majority of popular imitation models are focused on constructing the systems that are capable to execute certain set of functions *better* than humans do. In this process, the priority refers to *reliability, effectiveness* and *processing speed* of the models proposed. Nevertheless, presently it becomes clear that this approach is not completely relevant for modeling just the human cognition. Actually, a human person, being posed to various real situations, should be able to solve a lot of various problems (including the ill-posed ones). Thus, the priority is to be given to the ability to “survive”, i.e., to *adapt* to unexpected and unpredictable situations. Therefore, a human-level cognition is *uncertain,* often *unpredictable*, and always *individual.* The enigma of individuality (in particular, of the artificial systems) is really the challenge for modeling a cognitive process.

Regarding human-level cognition, one cannot ignore the role of emotions. There are numerous attempts to consider the emotional component in modeling the cognitive process (e.g., [13, 14, 20]). However, the exact mechanism of emotion emergence, as well as the character of mutual influence of cognitive and emotional components were not revealed.

Another key problem in the cognition modeling concerns the imitation and interpretation of the logical and intuitive thinking. It is close to the “enigma of two hemispheres”: why a human brain is splitting into two constructively similar but still not identical parts. The hypothesis has been put forward (and became popular) that the right hemisphere (**RH**) is responsible for learning, while the left one (**LH**) does operate with the well-known information [7]. Below, it will be shown that this hypothesis is in entire agreement with our inferences.

Note that there is no unambiguous definition of the cognitive process. Within NCA, the cognition is treated as a *self-organizing process of recording, storing (memorization), coding, processing, generating, and propagating the “self” information.*

In the present work, we propose a particular version of cognitive architecture designed within NCA to perform these functions.

2 Theoretical Foundation of NCA

2.1 Dynamical Theory of Information (DTI) as Applied to Cognitive Process

– The definition [19]: *information is the memorized choice of one version among a set of possible and similar ones*. This definition does not contradict to others, but gives an idea of ***how*** the information might emerge;
– The choice could be made as a result of two different processes, namely—*reception* (superimposed choice) and *generation* (free choice) of information.

These processes are *dual* (complementary), thereby, these functions are to be shared between just two different subsystems (below: hemi-systems).
- The process of generation of information could proceed only in the presence of chaotic (casual) element, commonly called the *noise*.
- Depending on ***who*** makes the choice, there appear: *objective* information (the choice made by Nature, i.e., physical principles) and ***conventional*** information (the choice made by certain *collective*). This choice is not *the best* but *individual* for a given group.

2.2 Neurophysiology Considerations

- Neuron is a complex structure not reduced to a simple adder of signals, as it is accepted in standard neural processors. Within NCA, we use a continual representation for the *dynamical formal neuron* [2]—a particular case of the FitzHugh-Nagumo model [6, 17].
- Emotions are controlled by the level and composition of *neural transmitters* inside the human organism.

2.3 Neural Computing

- The neural processor represents a plate populated by the *dynamical* formal neurons described by the nonlinear differential equations [2, 3].
- Imaginary information should be recorded and stored within the Hopfield-type [12] processor (*distributed* memory) providing associative correlations.
- Recording the information (learning) requires Hebbian training mechanism: initially weak connection become stronger ("blacker") in course of the learning process [11].
- Storage and processing the well-known information (recognition, prognosis, etc.) require the training rule proposed by Hopfield [12]: all connections are initially equal and strong; during the training process the "irrelevant" connections are gradually *frozen out* (the principle of "redundant cut-off").
- The conversion of an image into *symbol* is to proceed in the localization Grossberg-type [8] processor with nonlinear competitive interactions. This provides the choice of single neuron (symbol) to represent all the information on a given image. Here, the paradigm "Winner Take All" should be realized [15]. Within NCA, this process should be *unstable* to secure unpredictable symbol position. This feature secures the *individuality* of a given system.
- After the given *G*-neuron became the *symbol*, it should be eliminated from the competitive struggle and acquires the possibility to cooperate with other neuron-symbols to form the *generalized* image ("image-of-symbols"). Free G-neurons could compete only.

3 Cognitive System Architecture

3.1 Main Constructing Principles

The version of NCA architecture presented in Fig. 1 has been worked out in the paper [2]. The main constructive feature of this architecture consists in splitting the whole system into two (similar) hemi-systems: **RH** (Right Hemi-system) containing the noise, and **LH** (Left Hemi-system) free of noise. The terms are chosen to correlate conventionally with cerebral hemispheres. The noise in **RH** provides generation process, i.e. production of *new* information and *learning*. **LH** is responsible for reception and processing the already known (learned) information. This specialization, being the theoretical result of DTI principles only, surprisingly coincides with inference of practicing psychologist Goldberg [7]. This fact represents a pleasant surprise and indirect confirmation of NCA relevance.

All the connections in R**H** are training according to the Hebb's rule [11]: being initially weak, the connections become stronger ("blacker") during the learning process up to certain threshold value. Then the learned image is transferred to **LH**. In **LH**, on the contrary, all connections are trained according to original version of Hopfield [10] "redundant cut-off". Thus, **RH** provides the *choice*, while **LH** performs the *selection.*

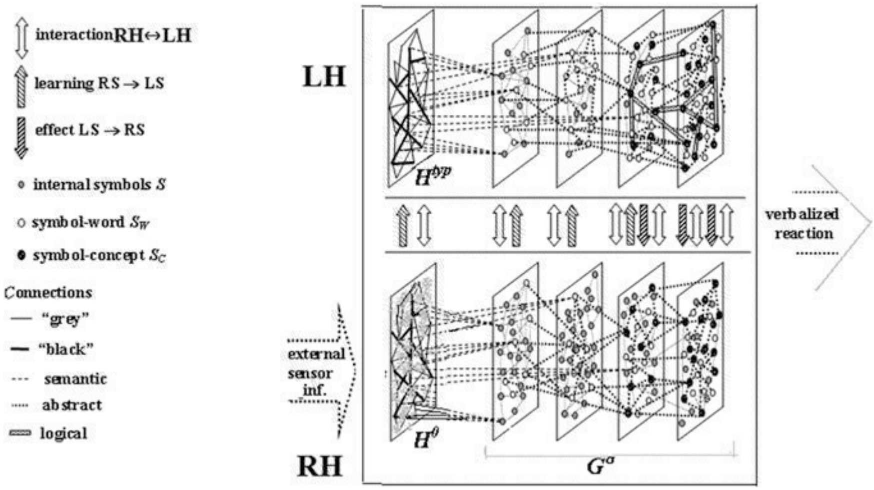

Fig. 1 Architecture of the cognitive system

3.2 Representation of Different Information Levels

The whole system represents complex multi-level structure that does evolve by itself (in Figure—from the left to the right) due to the self-organizing principle of "connection blackening". This implies that at each level, the elementary act of the image processing in **RH** and transferring to **LH** is repeated. In physics, there is special term "scaling" for such principle of organization, and the result is called a *fractal.* The system contains four basic elements.

- *Primary image **I*** at the plate $\boldsymbol{H}^{\mathbf{0}}$ include any available imaginary information: all signals from receptors are written as chains of activated neurons forming the ***images***. The inter-plane connections between neurons are modified from weak (grey) to strong (black) ones upon presentation of the objects. This level carries out the function of *recording* the "sensual" information and refers to **RH**.
- *Typical images **TI*** are presented at the plate $\boldsymbol{H}^{\mathrm{typ}}$ in **LH,** which perceives only the images recorded by strong enough (black) connections. Its functions are: to store useful information and filter out unnecessary one, and to recognize already learned images.
- *Symbolic* (*semantic*) *information—symbols **S*** correspond to *typical* images and are formed in **RH** (with the noise participation). Each symbol possesses a semantic content, i.e., awareness of the fact that this chain of active neurons describes a real particular object. At the same level one can find a ***standard symbol*** (symbol-word $\boldsymbol{S_W}$ that are presented in **LH** mainly) to indicate the same specific object. Symbols provide the interaction between the plates, i.e., processing of sensible information.
- *Abstract* (*verbalized*) *information*—whole infrastructure of symbols ***S***, standard symbols $\boldsymbol{S_W}$, and their interrelations. These items are not connected with neurons-progenitors on the plates ***H***, and thus, are not associated with any imaginary object, but appear in the well-trained system due to interaction of all the plates (the "deduced knowledge"). Its function is to implement a communication with other systems ("*to explain by words*") and comprehend the symbolic information. The highest hierarchy levels are occupied by the *generalized symbols*, or *symbol-concepts* $\mathbf{S_C}$, such as "conscience", "beauty", "infinity", etc. These symbols have no material content (real concrete object), but do have sense for a given system.

3.3 Interpretation

The emergence of each subsequent level is accompanied by a *reduction* of information. So, primary images recorded by weak (grey) connections are not transferred to $\boldsymbol{H}^{typ}$ level, and thus, could not be associated with any symbol—this information turns out to be neither conscious, not controlled by the system itself. This chain can be activated by noise only, what corresponds to an *inspiration* (the “aha moment”). The whole set of “grey images” could be treated as the *sub-consciousness*.

The lower levels of the architecture represent the *latent* (hidden) individual information of the system, the “thing-in-itself”. Only the higher levels, the *abstract verbalized* information make sense in the common meaning (“*to bring on the level of consciousness*”).

Note that the *latent* (hidden*)* information has its own “levels of depth”, with the bulk being stored in **RH**. This very information could be interpreted as the basis for *intuition*. The *logical* thinking should be related to *verbalized concepts* and *abstract relations*, but those that are common for a given society. It refers to **LH** only.

4 Representation of Emotions

4.1 The Problem of Emotion Formalization

Incorporating the emotions into artificial cognitive system represents really the challenge, since emotions have dual nature. On the one hand, they represent *subjective self-appraisal* of the current/future state. On the other hand, emotions are associated with *objective* and experimentally *measured* composition of neural transmitters in the human organism. The latter is controlled by more ancient brain structures (so called “old cerebrum”) than the neocortex. Since the cognitive process is commonly attributed to the neocortex, the realization of mutual influence of these structures requires special efforts. Thus, there is the same explanatory gap, as between the concepts of brain and mind.

In psychology, the self-appraisal (emotion) is ordinarily associated with achieving a certain *goal*. Commonly, they are divided into positive and negative ones, with increasing probability of the goal attainment leading to positive emotions, and vice versa. Furthermore, it is generally known that any *new* (*unexpected*) thing/situation calls for *negative* emotions, since it requires additional efforts to adapt. Our representation of emotions relies on this concept as well.

In neurophysiology, emotions are controlled by the level and composition of the *neurotransmitters* inside the organism. The entire variety of neurotransmitters can be sorted into two groups: the *stimulants* (like *adrenalin*, *caffeine*, etc.) and the *inhibitors* (*opiates, endorphins*, etc.). However, there is no direct correspondence between, e.g., positive self-appraisal and the excess of either inhibitors, or stimulants.

According to DTI, emotions should be classified as *impulsive* (useful for generation of information) and *fixing* ones (effective for the reception of information). Since the generating process requires the noise, it seems natural to associate impulsive emotions (*anxiety, nervousness*) with the *growth of the noise amplitude.* Vice versa, fixing emotions could be associated with *decreasing* noise amplitude (*relief, delight*). By defining the goal of the living organism as the maintenance of *homeostasis*, (i.e., calm, undisturbed, stable state), one may infer that, speaking very roughly, this classification could correlate with negative and positive emotions, respectively.

4.2 Main Hypothesis Concerning Emotion Representation Within NCA

Proposition 1 *The influence of neurotransmitters should be accounted for by the system of equations that link the noise amplitude Z(t) with the aggregated variable μ(t) that represents virtual composition (stimulants minus inhibitors) of neurotransmitters.*

Proposition 2 *The emotional reaction of human beings could be interpreted as the time derivative of the noise amplitude, i.e., dZ(t)/dt. The absolute value of derivative dZ/dt corresponds to the degree of emotional manifestation: drastic change (jump) in Z(t) imitates either panic (dZ/dt > 0), or euphoria (dZ/dt < 0), and so on. Note that this value could be either positive, or negative that could be (very roughly) related to negative and positive emotions, respectively.*

Proposition 3 *The same derivative should control the "dialog" between hemi-systems: increasing Z(t) (negative emotions) corresponds to activation of* ***RH****, while decreasing Z (t) (positive emotions) switches on* ***LH*** *activity.*

Basing on these propositions, we have elaborated the model for mutual influence of the "emotional" and "cognitive" factors [3, 4] that reveals a wide field for speculations and interpretations. Further study of this model seems promising.

5 Conclusion

The cognitive architecture designed within NCA represents a complex multi-level construction of different type neural processors, capable to perform the functions of recording, memorization, coding, processing and generation of the information. The emotions are treated as the variation of the noise amplitude that should help to activate or, vice versa, set at rest the cognitive process; they are inherently embedded into the system from the very beginning.

It should be stressed that the approach presented contains *three principle presumptions* that distinguish it from other ones. First, the main principles of DTI being applied to a cognitive process result in inference that the whole system *should by split into two* independent but linked hemi-systems for generation and reception of information, an analogy to cerebral hemi-spheres. Second, the process of generation of information requires *participation of the random element* (*noise*). Third, the learning principles in those hemi-systems *should differ*: generation of information requires Hebbian training rule, while the reception requires Hopfield-type training. These very features enable us to interpret and imitate the human-level cognitive features, namely—uncertainty, individuality, capability of intuitive and logical thinking, emotional effect on a cognitive process, etc.

However, there are still problems to be considered, such as social behavior, decision making, etc. Those problems deserve further research.

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Models of Autonomous Cognitive Agents

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Abstract The lecture describes current models of autonomous cognitive agents. The study of these models can be considered as the method of investigations of biologically inspired cognitive architectures (BICA). The main attention is paid to the models that are used at studying of cognitive evolution. Several examples of such models are outlined. Schemes of new models are proposed.

Keywords Models of autonomous cognitive agents · Modeling animal behavior · Evolutionary origin of human cognition

1 Introduction

One of the main methods of BICA investigations is the study of models of autonomous cognitive agents. We consider an autonomous agent as a modeled organism. The review [1] characterizes early researches of cognitive agents. Our approach is in close relation with investigations of cognitive evolution [2, 3]. The current lecture describes shortly the following models:

- the computer model of adaptive behavior of autonomous agents that have natural needs: food, safety, and reproduction [4];
- the model of formation of heuristics and generalized notions by the self-learning agent [5];

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- the models of agent movement in mazes, accumulation of knowledge, and formation of predictions [6];
- the model of plan formation of rather complex behavior [7].

In addition, we propose schemes of new models of autonomous cognitive agents that could do scientific discoveries [8].

2 Examples of Models of Cognitive Agents

2.1 Model of Autonomous Agents with Several Natural Needs

We believe that an agent has the needs of food, safety, and reproduction. We consider the population of agents. Each agent has the internal resource $R(t)$. The time t is discrete. Each agent is placed in a certain cell; there is a predator in the same cell. The predator activity varies periodically: after every T_p time moments, the active predator becomes inactive; the inactive predator becomes active. The active predator can reduce essentially the resource R of the agent that is in the predator cell.

There is the hierarchy of needs: the need of food has highest priority, the need of reproduction has the lowest priority.

Satisfaction of agent needs is regulated by means of three factors F_F, F_S, F_R, related to needs of food (F_F), safety (F_S), and reproduction (F_R). We believe that there is a threshold for each factor (T_F, T_S, T_R). If a certain factor is greater than the corresponding threshold, then the related need is satisfied. The agent has the leading need, which has the highest priority among unsatisfied needs.

The agent control system is a set of rules: $\boldsymbol{S}_k \to A_k$, where $\boldsymbol{S}_k$ is the situation, A_k is the action, k is the rule index. Each rule has its own weight W_k. The agent rule weights W_k are adjusted by means of the reinforcement learning [9]. The change of the factor of the leading need is the reward of the agent. The agent prefers the actions that correspond to large rule weights W_k. The situation vector $\boldsymbol{S}_k$ characterizes (1) the predator activity in the agent cell, (2) the previous agent action, (3) the leading need of the agent. The agent can execute the following actions: (1) searching for food, (2) to eat the food, (3) preparation for reproduction, (4) reproduction, (5) to do defense action, (6) to do nothing (to rest).

At eating food, the agent increases its resource R. At reproduction, the agent transmits an essential part of its resource R to its descendant. The agent-child inherits the rule weights W_k of the parent with small variations. If the agent executes the action "defense", it is protected from the active predator that is in the agent cell, whereas, the active predator reduces essentially the resource of the non-defensive agent.

The computer simulation demonstrates the cyclical behavior of agents. During the cycle, the agent firstly accumulates the internal resource (by eating the food), then the agent's actions are aimed at maximizing the safety and maintaining the level of internal resource, and when both needs (food and safety needs) are satisfied, the agent replicates (the need of reproduction is satisfied too).

Thus, the behavior of autonomous agents that have several natural needs has been analyzed. The model demonstrates the formation of cycles of behavior; the needs of food, safety, and reproduction are consecutively satisfied in these cycles.

2.2 Model of Formation of Heuristics and Generalized Notions by Self-learning Agent

One of the most important cognitive properties of living organisms is the formation of generalized notions. Using notions leads to a reduction in the required memory and the processing time. However, how do the notions emerge? Can we imagine the processes of formation of notions by means of computer simulation? We outline a computer model in which the autonomous agent alone produces generalizations and forms notions.

The model describes behavior of the autonomous agent in the two-dimensional cellular world. The control system of the agent is a set of rules: $\mathbf{S}_k \rightarrow A_k$, where $\mathbf{S}_k$ is the situation, A_k is the action, k is the index of the rule. Each rule has its own weight W_k. The vector $\mathbf{S}_k$ characterizes presence or absence of food in cells in the "field of vision" of the agent. The field of vision includes four cells: the cell, in which the agent is, the cell ahead of the agent and the two cells to right and left from the agent. The agent executes one of the following five actions: eating food, moving forward, turning to right or left, to rest. Portions of food are randomly placed into a half of the cells of the cellular world. The agent resource R increases at eating food.

Rule weights W_k are modified by means of the reinforcement learning [9]. Changes of the agent resource R are rewards at this learning. The reinforcement learning increases the weights of the rules, the use of which leads to an increase of the agent resource. The agent prefers the actions corresponding to large rule weights W_k.

The computer simulation demonstrates that the self-learning agent itself generates the following heuristics. The agent executes the action *eating food*, if there is food in the cell containing the agent (irrespective of presence of food in the other cells of the field of vision of the agent). The agent executes the action *moving forward*, if there is no food in the agent cell, and there is food in the ahead cell. The agent executes the action *turning to right or left*, if there is no food in the agent cell and in the forward cell, but there is food in the right or left cell from the agent. The frequency of the action *to rest* is negligible small.

In addition, the computer program included the averaging procedure. Namely, the average number of executions of certain actions for a given situation $\mathbf{S}$ was calculated. The averaging procedure results in creation of the following agent notions: *there is food in my cell*, *there is food in the forward cell,* and *there is food* *in the right or left cell*. Therefore, the agent itself is able to generate autonomously the notions, characterizing the sensory information.

2.3 Models of Fish Exploratory Behavior in Mazes

We designed and analyzed models of cognitive behavior of fish in the course of maze exploration. The models are inspired by the biological experiment on zebrafish, Danio rerio, in mazes [6]. Three types of models are designed and investigated. The model 1 describes how the fish acquires knowledge about arms of the maze. The model 2 characterizes fish's predictions of the next situation for the current situation and action. The model 3 is the hypothetical model of plan formation in a rather complex maze.

The model 1 assumes that the agent (modeled fish) has a certain knowledge K_i about each arm. When the agent visits i-th arm, the value K_i becomes equal to certain maximal value. Additionally, all values K_i slightly decrease with time.

The model 2 characterizes assurance of agent predictions. Namely, for the given initial situation S_t (each situation corresponds to a particular arm) and the action A_t (moving forward, turning to left or right) the assurance of the prediction of the next situation S_{t+1} is characterized by the value A_S. The values of assurances A_S are adjusted as follows. At the time step $t + 1$, the agent checks the prediction that it has made at the time step t. If the prediction of the next situation is correct, then the assurance of this prediction increases; if the prediction is wrong, then the assurance of this prediction decreases.

The model 3 assumes that after certain period of maze exploration, the fish is able to form some generalized notions that characterize the essential places (situations) in rather complex maze. The agent has knowledges about situations and reliable predictions of results of possible actions. The model 3 describes the process of forming the plan of movement to the goal situation, which was not visited for a long time (such situation has the minimal value of knowledge K_i). The agent creates a plan of movement from some starting situation to the goal situation.

The agent creates this plan as follows. Using the table of reliable predictions, the agent begins to analyze such situations and actions that result in the goal situation. Then the agent analyzes situations and actions that result in the pre-goal situations, and so on. Thus, *the agent begins from the goal situation* and analyzes consecutively possible ways to reach this situation. The agent also takes into account the distance from the considered situation S_t to the goal situation; this distance is the number of actions needed to reach the goal situation from the situation S_t.

Then the agent creates a simple *knowledge database* that is a table. Each row of this table includes the following information: (1) the given situation, (2) the action that reduces the distance between the given situation and the goal situation, (3) the next situation that is the result of the action and (4) distances between the given/next situations and the goal situation.

Finally, using this knowledge database, the agent forms a plan of movement from *the starting situation to the goal situation*. In this process of plan formation, the agent consecutively selects actions, which reduce the distance between the considered situation and the goal situation.

Thus, the models of accumulation of knowledge, prediction of results of actions, and planning of movement towards the goal situation have been developed and investigated.

The similar model of planning by New Caledonian crows is outlined below.

2.4 Model of Plan Formation by New Caledonian Crows

The model is based on the biological experiment on New Caledonian (NC) crows [10]. In that work, NC crows were preliminary trained to execute particular elements of a rather complex behavior. After the preliminary training, the crows should solve the three-stage problem that includes the following particular elements:

1. to pull up a short stick tied to the end of a string and to release this stick,
2. to extract a long stick from a barred toolbox by means of the short stick, and
3. to extract the food from a deep hole by means of the long stick.

It was impossible (a) to extract the food from the deep hole by means of the short stick and the bill, and (b) to extract the long stick from the barred toolbox by means of the bill. Therefore, in order to reach the food, the crow had to execute the ordered chain of sequential actions $1 \rightarrow 2 \rightarrow 3$.

Similar to the model of plan formation by fish, the agents (modeled crows) use the predictions of results of particular actions to create a *knowledge database*. The predictions were obtained during the preliminary training. The agent knowledge database characterizes situations, actions, results of actions, and distances between considered situations and the goal situation. The agent uses this knowledge database at forming the plan of solving the three-stage problem.

The process of plan formation was observed at computer simulation. See [7] for details.

The next section describes the scheme for future modeling of the autonomous agent-physicist (artificial scientist).

3 Proposal for Modeling of Autonomous Agent-Physicist

The proposal is based on the fact that *the most serious cognitive processes are processes of scientific cognition*. The background of this proposal is the report by Modest Vaintsvaig at the Russian conference "Neuroinformatics-2011" [11]; that report considers the models of an autonomous agent that tries to cognize elementary laws of mechanics. The agent observes movements and collisions of rigid bodies. Basing on these observations, the agent can generalize its knowledge and cognize regularities of mechanical interactions. Therefore, modeling of such autonomous agents, we can try to analyze, how agents could discover (by themselves, without any human help) elementary laws of mechanics. Ultimately, such agents could discover three Newton's laws of mechanics. Thus, we can investigate autonomous agents that could come to the discovery of the laws of the nature.

Using our knowledge about scientific activity of Isaac Newton, we can represent intelligence of such investigating agent in some details. The agent should have an aspiration for the acquisition of the new knowledge and for the transforming of its knowledge into compact form. The agent should have the curiosity that directs the agent to ask the questions about the external world and to resolve these questions by executing the real physical experiments. The agent should take into account the interrelations between different kinds of the scientific knowledge. It is natural to assume that a certain society of cognizing agents exists; the agent of the society informs other agents about its scientific results. For example, considering Isaac Newton as a prototype of the main agent, we can consider also agents that are analogous to Galileo Galilei, Rene Descartes, Johannes Kepler, Gottfried Wilhelm Leibniz, Robert Hooke. The agent should have the self-consciousness, the emotional estimation of the results of its cognition activity and the desire to reach the highest results within the scientific society. Agents should have the tendency to get the clear, strong and compact knowledge, such as Newton's laws or Euclidean axioms.

4 Conclusion

Thus, simple models of autonomous cognitive agents have been described. These models characterize initial steps of modeling of cognitive evolution [3]. The scheme of new models of the autonomous agent-scientists, which could cognize the nature, has been proposed.

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Differentiation of Groundwater Tax Rates as an Element of Improving the Economic Mechanism in the State Groundwater Extraction Management

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Abstract Since Russia has rich resources of fresh underground waters, one of the major practical problems in their fund managing is a rational use of its resources and protection of aquifers from contamination and depletion. Economic instrument in the structure of state groundwater extraction management is a system of taxation. Modern system of groundwater extraction taxation is currently imperfect and has definite drawbacks. Among them are: incorrect system of tax rates for underground waters usage, budget deficit, that shifts to other areas of the national economy. The purpose of this article is the improvement of system of groundwater extraction taxation, which should be directed to the state for reimbursement of expenses for groundwater exploration, monitoring, and should provide differentiation of water tax rates, depending on hydrogeological characteristics of aquifers, types of water users and other parameters.

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1 Introduction and Related Works

Groundwater is classified as strategic mineral, along with hydrocarbon resources [10], so drinking water supply will become one of the urgent problems in modern society. According to UN experts, by 2030, about half of the world's population will suffer from a shortage of fresh water [11]. The territory of Russia has more than 20 % of world's reserves of fresh water, which makes it in this regard, one of the richest countries in the world [8]. The most promising source of drinking water supply is groundwater usage. Drinking and industrial groundwater is one of the most important components of the groundwater mineral resource base in the Russian Federation [7]. They are used to provide water supply to the population and the regional economy. According to official statistics, the share of groundwater use in overall balance of drinking water supply is 53–55 % [1]. Predicted reserves of drinking and technical groundwater of the Russian Federation are very large; they are estimated at 869.1 million m^3/day [7].

The current structure of water resources management in Russia is complex and "formless". Such issues as structuring of the management authorities, including clear delineation of roles, rights and responsibilities in organizations, as well as the division of competences among them; preparation of the legislative framework; development and implementation of economic mechanisms and methods in economic stimulation of rational groundwater usage should be solved in the course of water management restructuring [2].

Any changes in the system of state regulation of groundwater fund in Russia are impossible without improving the economic aspects of groundwater use, namely pricing and taxation system of groundwater extraction [6]. Current imperfect taxation system objectively counteracts the intensive reproduction of mineral resource base, integrated and rational use of groundwater [3]. Finally, the collection of groundwater tax does not provide even the current expenses of the state for monitoring and exploration. Therefore it is necessary to propose a new system of taxation, which depends on various parameters. Collection of groundwater tax should provide a self sufficiency for groundwater extraction branch and bring it from the category of the subsidized sectors in the national economy.

Development and improvement of groundwater extraction taxation through the use of differential calculation of groundwater tax rates for different categories of water users are the purposes of this article. There will also be an illustration of the calculating principles in the tax formula for a variety of parameters included in the proposed dependence.

2 The General Principle of Groundwater Tax Calculation

Nowadays, water tax has been provided for water that is being taken from surface and underground water and it depends on the economic regions of the country [9, 10]. What is more, tax rate is being differentiated by river basins and lakes in each economic region. At the same time, tax rates for underground water is also being differentiated by river basins and lakes, while this method is incorrect because one river basin can be discharged in several aquifers [5]. Furthermore, the geographical distribution of aquifers may affect multiple river basins. Each aquifer has its own properties, such as hydrodynamic characteristics, recharge and discharge zones, individual hydrochemical composition etc. That's why speaking about the main aspects in managing the extraction of groundwater, it is advisable to build a system of taxation in connection with the operation of individual aquifers or aquifer systems, taking into account their characteristics and geographical location, using a single tax rate for each aquifer [4].

Tax rate for the population water supply is 1.16 euros for 1000 m^3 of water. This tax rate is being indexed in association with the anticipated inflation ratio. However, total indexed rates of water tax without taking into account the peculiarities of the aquifer systems is contrary to the principle of respect to groundwater as unique useful fossil, and leads to averaging of aquifers, while they are different in their qualitative and quantitative characteristics.

One of the key problems in the system of groundwater taxation is water extraction account. Not all the groundwater intakes are equipped with water measuring meters, and those objects who have them, can easily be "got round". Especially, it is difficult to organize extraction account (calculation) for law-debit wells having a simple system of water piping for former and draw-wells, where it is impossible to take into consideration volumes of groundwater extraction. The same issue can be remarked with capping springs and overwhelming majority of private wells.

Solution of this problem can be found with application of water tax rate for estimated exploitative reserves of the intake. This parameter characterizes the size of stated water demand that can be extracted from the intake for the accounting period of time. When a license for groundwater extraction is granted, quantity of estimated exploitative reserves is the main parameter in al the hydrogeological calculations, including protective sanitary zones. Accordingly, directly this parameter is the key one during the calculation of water bearing stratum resource potential. Volume of groundwater extraction on the concrete water intake is subtracted from the total quantity of groundwater potential.

This principle of application of water tax rate for estimated exploitative reserves is similar to imputed tax. Quantity of water that is declared by the water consumer for supply will be taken into account in the calculating of water tax. For law-debit and individual wells it is advisable to calculate water tax rate due to the safe standards for drinking water (SanPin) for each region. Application of this approach will make people treat to exploitative reserves estimation, adequate request for water consumption and economy of mineral resources with special care. In the case of excess quantities of water consumption than values of estimated reserves water extracting company or individual person should feel responsibility that can be influenced by penal sanctions for resource overage. Herewith the role of state monitoring increases. Besides their functional purposes—collection of annual reports, control survey of groundwater intakes can be added.

The present system of water tax rates does not give any opportunities to the state as owner of mineral resources to make any revenues for the provision of such a valuable mineral as groundwater. Therefore new formula and algorithm for groundwater tax calculation are being proposed in this article. The basic variables of this formula are:

- The category of water user;
- The category of groundwater resource value;
- The category of complexity of the geological structure and hydrogeological conditions of the resources;
- The cost of ready-to-use groundwater (SST);
- Average regional water rates;
- The equity ratio (use factor).

Such parameters have been selected on the principles of hydrogeological zoning, aquifers' common characteristics and current criteria for the assessment of the extraction cost and treatment of groundwater.

The benefits that are being provided by these parameters are:

- Easy application;
- Official data (including statistics, monitoring of State Commission on reserves, etc.);
- Applicability of differentiation (based on the properties of the unique aquifers, types of water users etc.);
- Incentive effect (in terms of the water use disciplining);
- Conservation of groundwater resources;
- Generality: the ability to use collected water tax to finance "geological control" and the initial stage of exploration based on the conditions and characteristics of any region;
- The opportunity to supplement the methodology with new innovative technologies in geological prospecting.

The proposed formula for water tax calculation is as follows:

$$N_{\mathrm{full}} = \left(\frac{k_1}{n_1} + \frac{k_2}{n_2} + \frac{k_3}{n_3} + \frac{\lg(\alpha)}{\lg(\alpha_{\max})} + \frac{T - C_r}{T} + 1\right) \cdot N_{\min},$$

k_1	The category of water user;
k_2	The of category groundwater reserves;
k_3	The category of complexity of the geological structure and hydrogeological conditions of the resources;
n_1, n_2, n_3	Scale factors;
α	The equity ratio (use factor);
C_r	The cost of ready-to-use groundwater;
T	Average regional water rate;
$N_{\min}$	Minimum starting water tax rate.

Let's consider all variables, that were highlighted before.

(a) The category of water users consists of 6 categories in depend on the water user needs and class. That means that $k_1 \in [0, 5]$, while $n_1 = 5$.
The properties of the k_1 variable:

- the lowest rate—for individual users,
- the highest rate of commercial water users (for commercial bottling),
- the category of water user is being assigned at registration of the license for prospecting and evaluation hydrogeological research.

(b) The category of groundwater reserves includes four categories: A, B, C1, C2. Therefore $k_2 \in [0, 3]$.
The properties of the k_2 variable:

- characterizes the reliability of the aquifer parameters,
- describes risks associated with the extraction of water from this aquifer,
- water users are being assigned when the license is being obtained,
- revaluation of the groundwater reserves may be done on the basis of the experience groundwater extraction.

The higher the category of groundwater resource value, the lower the water tax. The water tax should encourage water users to increase the category of groundwater resource value. Thus, the hydrogeological study exploration of underground water by water user is being stimulating.

(c) To consider the category of complexity of the geological structure and hydrogeological conditions of the resources it should be mentioned that this variable is determined by:

- boundary conditions of aquifers;
- the groundwater protection degree of protection of;
- the variability in chemical composition of groundwater;
- external human-induced factors;
- supply conditions of the aquifer, interaction with other aquifers, the discharge parameters, etc.;
- reference data from the monitoring reports on the basis of exploration.

There are four categories of complexity of the geological structure and hydrogeological conditions of the resources. That is why $k_3 \in [0, 3]$. For example, if the complex hydrogeological conditions is being included into the group 4 of the Classification of resources and predicted resources of drinking, technical and mineral underground waters, the variable will equal zero.

(d) The cost of ready-to-use groundwater variable calculation is based on:

- costs for geological exploration up to C1 category (S_g);
- costs on the intake construction (S_i);
- the cost of the water intake operation for 25 years (S_e);
- the cost of water treatment for the entire period of operation of water intake (S_t);

- the cost of transporting underground water to the point of distribution (S_d);
- total declared production of water in 25 years of intake operation (V).

$$C_r = \frac{S_g + S_i + S_e + S_t + S_d}{V}$$

C_r extends the average setting for the entire aquifer or aquifer area with similar characteristics of composition and technological characteristics of groundwater extraction.

The higher production and preparation costs of groundwater are, the lower water tax will be.

(e) Parameter regional average water tariff can not be regarded as an objective price of water as being a socially important parameter; it reflects not only the value of water but the consumers welfare level. Water tariffs are determined at the regional level, approved by the territorial committee of tariffs. In general, the rate depends on the solvency of the population in the region.

(f) The equity ratio (use factor) of underground water is determined by the ratio of the total resource potential estimated in the framework of the deposit to the limit value of water consumption, stated in the license. And it is determined by the formula:

$$\alpha_{gen} = \frac{Q_R}{Q_L}$$

Q_R the total estimated resource potential of the deposit, m^3/day
Q_L the permitted water extraction limit, m^3/day.

This parameter is used in the official accounting system of groundwater monitoring service.

With high prosperity of permitted water withdrawal coefficient α may be larger and much larger than 1. Accordingly, requirements for quality of hydrogeological studies at the exploration stage, and at the stage industrial exploitation are increased. With a large number of water users declining water level could happen.

This factor may also affect the mechanism of state regulation. For example, at low supply water users can use alternative sources of water supply (for household purposes). The higher the equity ratio (use factor) is, the greater water tax will be.

All these factors have official confirmation of values, based on the registration procedures for licensing, and are defined according to the status of water users and hydrogeological characteristics of the aquifer.

Analyzing a part of the target costs for the implementation of the first stage in geological exploration (geological survey) and monitoring of groundwater in the Leningrad region, comparative conclusions can be made.

1.48 million euro ($\sim$103.7 million rubles) in total was allocated to perform works on geological study and reproduction of groundwater mineral resources base at the expense of the federal budget funding in 2012–2014. In addition, monitoring costs amounted to 0.06 million euro ($\sim$4.4 million rubles) per year, so that is for 3 years, this sum is equal to 0.19 million euro ($\sim$13.2 million rubles). Total costs for exploration and monitoring for 3 years amounted to 1.67 million euro ($\sim$116.9 million rubles). Groundwater extraction for 2012–2014 years was $\sim$308,487,000 m^3 over three years. Consequently, all the costs of the federal budget amounted to 0.005 euro ($\sim$0.379 rubles) per 1 m^3 of extracted groundwater. The current tax rate is 0.001 euro (0.08 rubles) per 1 m^3 of groundwater. That is the current collection of water tax, which may not offset the costs of the federal budget for the sectoral programs.

An example of calculating the water tax rate on the main aquifers of the Leningrad region. The calculation is performed only for the boundary conditions—that is, the lowest and highest categories of reserves, the worst and the best of the hydrogeological conditions, extreme extraction volumes from the classes of water users.

3 Conclusions

The proposed water tax collection method at the maximum values of the parameters was 0.522 million euro (36,569 million rubles), at minimum—0.225 million euro (15.770 million rubles). The current collection of water tax on the main aquifers of the Leningrad Region at the current rate is 0.089 million euro (6.239 million rubles).

In this case, the method takes into account the classification of water users and hydrogeological characteristics of aquifers. For example, in the Vendian aquifer individual water user with complex hydrogeological conditions, lower categories of reserves has a tax rate of 0.003 euro (0.21 rubles) per 1 m^3 of groundwater. And commercial water user (for commercial bottling), extracting the same Vendian aquifer with high categories of reserves, simple hydrogeological conditions has a tax rate of 0.007 euro (0.47 rubles) per 1 m^3 of groundwater.

Thus, the size of water tax rate varies from 19 to 50 kopecks per 1 m^3, depending on the factors of extraction and main hydro-geological conditions. Changes of the basic minimum tax rate depend on the rate of inflation; calculated tax rates will vary accordingly.

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Users' of Information Systems Protection Analysis from Malefactor's Social Engineering Attacks Taking into Account Malefactor's Competence Profile

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Abstract Great attention of specialists information security given to the protection of software and hardware components of the information system, while users of the information system has been neglected and may violate the confidentiality of corporate data. The article considers the addition of the complex "information system—personnel—critical documents" with the competence profile of the attacker.

1 Introduction and Related Works

Computer systems that store and process information, are widely used in different industries and services. Such a wide spread of information technology makes a focus on information security. Nowadays, attacks on information systems have

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become more frequent, bring more losses and require more time and resources to identify those, who are responsible for such crimes. In 2014, global survey has been held by the United States companies. It showed that the average size of the US companies losses from cybercrime has increased by more than 9 %, to 12.7 million. In a study in 2013, this value was $11.6 million. Average time investigate attacks on information systems, also increased. Now it is 45 days compared with 32 days in 2013 [8].

Currently, much of the research in the information security are dedicated to the improvement of technical base of information security [6, 7, 13, 14]. These issues of information security are well understood, developed a large number of methods that minimize the probability of success of a malefactor's attacks. The term "information security" is often understood as the protection of information using software and hardware solutions [10]. At the same time, the influence of people also plays an important role in the information protection [1, 4, 9]. User of information system, which has access to critical documents is one of the most vulnerable links in the system. According to [5], the human action is the most common reason of information security incidents. One of the most effective attacks on information security is corporate espionage. More than a quarter of companies were subjected to corporate espionage and in almost 80 % of the cases the malefactor had a success [5].

An employee who has access to confidential information can compromise the security of information (confidentiality, integrity or availability) intentionally or unintentionally [10]. It should be noted that employees who are users of information systems are usually familiar with other employees who maintain or use the information system; they have access to documents that are stored in the information system; they may know the passwords of colleagues; they have physical access to certain computers. Therefore, the interaction of users of information system with malefactors may cause serious damage to the company.

The damage from a successful attack on information system can lead to serious consequences. In Russia, the average damage for companies SME from a serious incident is 20,000 dollars. Average damage of large enterprises can reach 350,000 dollars [5].

Thus, the problem of information security and protection of users from the social engineering attacks has recently reached a notable level of significance. Research in this area will help to expend a multi-level security systems with the users' protection layer, that will help the users of information system to resist malefactor's social engineering attacks more successfully. That will definitely led to the increase of the protection level of the confidential data, that is stored in information system. At the same time, it should be mentioned, that the problem of estimating a protection rate of whole information system and users of it system from the social engineering attacks is really complex. For this reason, the first thing, that should be done in this area is to develop methods for estimating the protection rate of the user from social engineering in a basic situation when we consider only one attack action of the malefactor on the only one user of information system.

The paper aims at the presenting an approach to the estimation the protection rate of user of information system from the malefactor's social engineering attack action. This approach renders to the evaluation of the probability of malefactor's attack action success, based on the given user's vulnerabilities and malefactor's resources.

2 "Informational System—Personnel—Critical Document" Complex (ISPCD)

Paper [2] was devoted to the description of ISPCD model. Software and hardware devices are being included to the informational system models of ISPCD complex. Each device model is being associated with the model of critical documents, which are stored on these devices or may be accessible through these devices.

Informational system's personnel models are also included in this complex. These models are described through different indicators such as access rights, post and some other. Key difference between model of an information system with personnel and model of an information system without personnel is that, as a rule, impact on the personnel (users of the information system) has nondeterministic character. The success of the malefactor's social engineering attack action on the user of an information system has probabilistic character. User's vulnerabilities profile (UVP) was developed for better estimation of the success probability of the malefactor's social engineering attack action on the user of an information system [11, 12].

As a usual, malefactor has limited resources, lack of knowledge and competence. These contingencies is illustrated thorough malefactor's competence profile (MCP), which is being described in this article.

If the described models are built and these parameters are specified, it is possible to estimate the indexes of the individual user's protection, and also the separate critical documents protection indexes. In this case, calculation will be reduced to the computation of the compound events probability and, based on them, the expectation values (for example, the mathematical expectation of damage from malefactor's social engineering attack impact, or the probability of not affection some critical document).

3 "Critical Documents—Informational System—Personnel—Malefactor" Complex (CDISPM)

Paper [2] was devoted to the presentation of two malefactor's social engineering attacks imitation models. They include imitation on the user's social graph and imitation on the ISPCD complex. These models allow to estimate the protection rate of the information system's users from the malefactor's social engineering attack on the basis of the users' links. At the same time, these models have some shortcomings, they do not include MCP. It is proposed to consider CDISPM complex instead of the ISPCD complex. This step will increase the accuracy of protection rate estimates of the users of information system from the malefactor's social engineering attack estimation due to the probabilistic assessments of malefactor's actions.

Why should be taken into account both the malefactor and the user? The importance of studying the features of both sides of the interaction—who affects, and who is affected,—emphasized in the scientific literature. Widely known expert in the field of influence psychology Robert Cialdini in his paper [3] noted that to study psychology concessions he began with a series of experiments to figure out what principles and characteristics are the basis for compliance in relation for requests or demands, but he soon realized that it is essential to study also the second side of the process. He called these people "professional concessions", as they know how to build cooperation, so that the other person gave in and complied with the request or requirement. This type of people has their basic need in the getting others to give in, as it will determine their life success. Cialdini R. as a result of their observations displays six basic influence principles: the principle of consistency, the principle of mutual exchange, the principle of social proof, a principle of authority, the principle of benevolence, the principle of scarcity. However, "personal financial interest" were not included to the main principles. Author regards them as "some axiom that deserves recognition, but not detailed descriptions".

MCP may be defined by the resources that are available for the malefactor, and be the social engineering attack action, that are known by the malefactor. Malefactor's resources include the time to conduct social engineering attack influence, financial resources for the staff's bribery implementation and some other characteristics. MCP also involves some personal characteristics of the malefactor, that ensure social engineering attack success, and also malefactor's ability to pick up and to carry out proper attack.

MCP can be represented as $((R_1, D(R_1)), \ldots, ((R_k, D(R_k)))$, where R_i is a resource, that is available for the malefactor, and $D(R_i)$ the quantity or volume of the resource, that is available for the malefactor. Social engineering attack actions are also treated as resources. In this case, probabilistic estimation of successful use of current social engineering attack by the malefactor are being considered as the resource amount. Time and financial resources those are available for the malefactor to conduct a social engineering attack action are also reckoned as resources, included in MCP.

Each malefactor's model has its own MCP with a unique set of resources. Thus, for each malefactor's model j MCP will consist of its unique resources and its amount $((R_1, D_j(R_1)), \ldots, (R_k, D_j(R_k)))$. While we have proposed such model of MCP, it is possible to proceed to success probability estimation of malefactor's social engineering attack action p_{ij}. Function, that represents p_{ij}, may be introduced in different ways. One of the possible way is as follows: $p_{ij} = \frac{D_j(R_i)}{M_i}$, where $D_j(R_i)$—the j malefactor's amount of R_i resource, M_i is a maximum amount of this resource, and p_{ij} is the probability of the success of j malefactor's social engineering attack action with the use of i resource. Thus, there is a transition from the amount of the resource used by the malefactor, to the probability of success of the social engineering attack action on the user. MCP may be introduced as $(p_{1j}, \ldots, p_{kj})$. In this simplest model we do not take into account the UVP and its influence on the probability of the success of social engineering attack action.

We consider, that each malefactor act individually, and they are not allowed to use the resources and results of each other.

As it has been already mentioned, models of each user of information system are being associated with the UVP. UVP includes the severity of user's vulnerabilities. On the basis of these severities probabilistic estimates of success of malefactor's social engineering attacks are being developed. It is assumed that the including of MCP will improve the accuracy of probability of social engineering attack success.

To sum up, it is possible to estimate different probabilistic assessment of the success of social engineering attack, which are implemented by different malefactor's models. The success of social engineering attack action of j malefactor will be determined not only by the amount of the available resources, but also by the severity of user's vulnerabilities. One of the possible options of representing the calculation function of estimation the success probability of social engineering attack of malefactor with predetermined MCP and UVP will be: $p_{ij} = \frac{D_j(R_i)S_k(V_l, R_i)}{M_i B_l}$, where $D_j(R_i)$ is the amount of malefactor's j R_i resource, $S_k(V_l, R_i)$—severity of the user's k vulnerability V_l, which may be influenced by the R_i resource, M_i is a maximum amount of R_i resource, B_l is a maximum severity of vulnerability V_l, and p_{ij} is the probability of success of social engineering attack action of j malefactor on the k user with the use of i resource. The distribution schedule for a given probability of success of social engineering attack may be implemented as it is shown in Fig. 1.

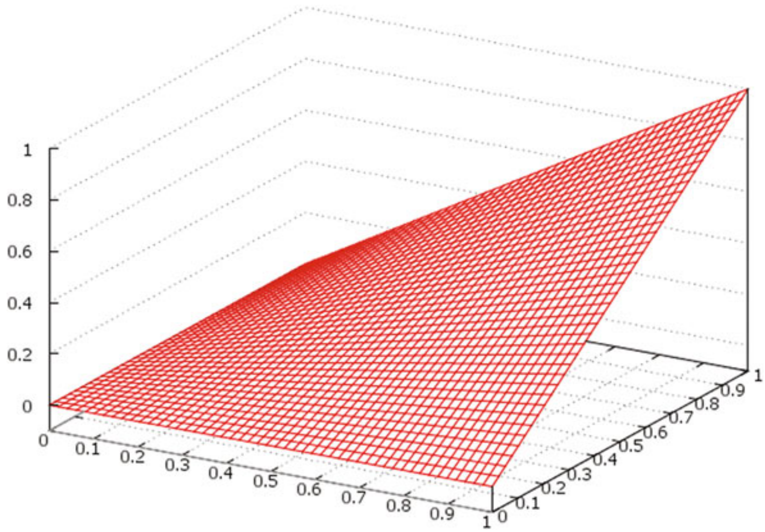

Fig. 1 Schedule distribution of the probability of success social engineering attacks

It is important to note that the same resource can affect the different user's vulnerabilities. So, for example, financial resources can be used both for user's bribery, and for the generation of external appearance, contributing to the establishment of appropriate relations with the user.

4 Conclusion

In this article the addition of "information system—personnel—critical documents" complex was presented. Malefactor's competence profile was introduced to this model. MCP allows to clarify the probabilities of malefactors social engineering attack actions.

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Character Reasoning of the Social Network Users on the Basis of the Content Contained on Their Personal Pages

Tatiana Tulupyeva, Alexander Tulupyev, Maksim Abramov, Artur Azarov and Nina Bordovskaya

Abstract The present research deals with the possibility of social network users value orientations reconstruction based on the information contained on the their personal pages. In the first part of the research 126 participants were included. They were students with the average age of 22, 39 % men and 61 % women. During the second part of the research more than 1300 posts published during 15.09.2013 and 15.03.2014 by the 39 users of social network were analyzed by the experts on the basis of developed classification. 89.7 % of respondents connect to the social networks more than 1 time a day and usually serf social networks for a 5 h a day. The study revealed that the expression of users' value orientations can be associated with a number of quantitative indicators, namely, with the frequency of the publication of posts of different types. The paper presents the dynamics of typing posts. Firstly, twelve types of posts were developed. They included: emotional, advertising, entertainment and reasoning posts. Emotional posts are usually published by the users who has some requirements in love; advertising and entertainment posts usually posted by people who has some requirements in fun and entertainment; reasoning posts can be often observed on the personal pages of users, who has a requirement in the strengthening friendly relations, spiritual and moral self-improvement and a low

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need in a strong family. Further analysis led to a qualitative change in the classification of posts with the release of the three dimensions of posts: informational, emotional, motivating and separation some subclasses among them.

1 Introduction and Related Works

The development of the information technologies nowadays leads to the introduction of these technologies into the day-to-day life of every person. It means that the study of characteristics of a person, particularly a young person, is now become possible by analyzing the information from their personal social media accounts [5, 9, 10]. The ambiguity of influence of the processes of virtual communication on the value orientation of young people is also a cause of significant interest to study this problem. One of the most perspective ways to study this problem is the analysis of Internet content users of social networks. For example, the value orientation of youth is a relevant research topic for a long period [7, 8]. Changing the basic values of society raises serious concerns of psychologists and sociologists. At the same time, highlighted specialists do not pay enough attention to the users of social network behavior. While the modern young people spend a lot of time surfing the NET. That is the main reason why without analyzing online-reality of users of social network there is no possibility to get a full information about person value orientation and his psychological features.

The aim of current paper is to reveal a number young people value orientations features, reflected in the posts of the social network users on their personal pages in the “VK.com” social network.

The word “post” is being treated in this paper as the message (text, photo, audio or video information, any other content), which is being published in the blogs, personal web-pages, forums etc.

2 Methods and Materials

To identify the needs of young people through the analysis of their personal accounts in social networks a pilot research was organized. It was decided to generate data in 2 ways: by interviewing respondents and processing their personal pages in “VK.com” social network [3]. The research consists of two parts.

In the first part of the research 126 respondents were interviewed. This group included 77 women (61.1 %) and 49 men (38.9 %), 79 respondents (62.7 %) has secondary school education and 47 (37.3 %)—high school education. The age of the respondents ranged from 18 to 39 years, the average age was 22 ± 3.8 years. All the respondents were students of different educational programs of first higher and second higher education. Respondents completed the survey, on the basis of the survey results the respondents’ behavior in social network and their needs were analyzed. The questionnaire included questions about user's preferences in social networks, openness of personal information on their personal accounts, the attractiveness of social networks, about time that is spent for surfing social networks, about categories of published posts, and about the existing needs. 12 categories of posts were proposed in this questionnaire to make respondents which categories he places on his personal page.

The analysis showed that further research of social network's content need to develop a classification that divides posts not only on disjoint types, but also has a 2-level categorization. Informational, emotional and incentive classes of posts and their subclasses were developed as a result of this analysis.

Experts held the second part of the research, where they analyzed the posts' content. Main task for the experts was to identify according to the updated classification. They have analyzed 39 users' personal pages in the "VK.com" social network, that included 1300 posts published since 15.09.2013 till 15.03.2014.

The design of the research did not involve collection and processing of sensitive information from personal pages of the respondents on social networks. Data that was analyzed in this research was the opened data, which users of the social network showed to the society. At the same time, respondents were requested to collect and process data from their personal pages. Only respondents who agreed with the proposal about processing their data told their web-pages. Plan of this research allowed to compare the characteristics of the content published on the respondents' pages in social networks with their personal characteristics, defined using some psychological techniques.

Results' statistical processing included calculation of the primary statistics (frequency of occurrence, average values of different parameters, their minimum and maximum values), and the application of the χ^2 test of goodness and Student's t-test for identifying the differences between subgroups.

3 Results and the Analysis

First part of the research showed that almost 100 % percent of the respondents prefer using "VK.com" social network. That is why "VK.com" has been chosen for further analysis. At the 2nd place on popularity there was "Facebook" social network, on the third—"Twitter". Thus, 3 main social networks, where the work with young people should be focused, have been identified. Furher analysis has shown that 90 % of respondents, who have "Twitter", also have a "Facebook" account. Coincidence of the intersection of audience of "OK.ru" social network and "Facebook" and "Twitter" was not detected. It was mentioned, that the "OK.ru" and "Facebook" social networks is different.

Significant differences between some subgroups of respondents were revealed. Twitter is more commonly used by the students, who receives first high education rather than people who has already graduated from University ($p < 0.04$). "OK.ru" social network is more often used by the women rather than men ($p = 0.003$).

The frequency of respondents output in the social network was also valued. 89.7 % of the respondents connect to the social network more than one time per day. 94.9 % of students, who receives first high education connect to the social network more that one time per day. Time, that is spent by the respondents surfing social network varies from 20 min per day to the 20 h per day. The average time of surfing social networks is 5 h per day. 23.8 % of respondents has a second account at the same social network, where the first one is (25.3 %—students, 21.3 %—people, who has graduated from university). Acquired data shows that significant part of their life students spend surfing social networks. That is why it is essential to take into account data from social networks while planning any activities with the youth.

The majority of respondents are attracted by social networks as they provide the opportunity to communicate with people and do not think about distance between them, watching videos, and listening to the music, as well as obtaining information about friends and their interests.

The differences between subgroups were also observed in the attractiveness of social networks to different people. Games and applications are more attractive to people, who has graduated from the university, than to the students ($p < 0.03$). Browsing photos in social networks is more attractive to women rather than to the men ($p < 0.03$).

Further, the respondents were offered a list of posts that users place on their page: in the questionnaire was required to note which posts are placed from the point of view of their subjects (Table 1). Most posted positions are entertaining, least—posts in which something is sold.

Further, the respondents were offered a list of posts that users commonly place on their personal page in the social network to make respondents to mark which types of posts they put on their personal pages. The result is being presented in Table 1.

Significant differences were identified. Posts containing advertising information about a product or service, often publish people with higher education than the students ($p < 0.03$). Entertainment posts (humor, jokes, fables) normally publish students ($p < 0.03$). Emotional posts are more likely to publish women, rather than men ($p = 0.01$). Quotes are mostly posted by women than by men ($p = 0.001$). Posts, “in which you are trying to show yourself or your closest people from the best side, or to demonstrate your (or your closest peoples’) achievements” normally publish women, if compared to men ($p = 0.005$).

Young users tend to post quotes with the statements of ancient philosophers, famous people or quotations from books, usually mentioning the author of the quote ($p < 0.05$); judgments, which reflect their point of view on important events or things ($p < 0.04$); posts, which show the users themselves or their closest people from the best side, or demonstrate users’ (or their closest peoples’) achievements ($p < 0.02$); entertainment posts (humor, jokes, fabels) ($p = 0.005$).

Respondents were asked to rank the following requirements in order of importance (“1”—the most important need today, “10”—the most insignificant): strong family; health; love; financial well-being; self- fulfillment; spiritual and

Table 1 Posts thematic structure

Post	Whole sample (%)	Sex (%)		Education (%)	
		Male	Female	Secondary	High
Entertainment posts	57.1	57.1	57.1	64.6*	44.7*
Citation posts (from famous scientists, actors etc.)	44.4	22.4	58.4	44.3	44.7
News posts	42.9	38.8	45.5	45.6	38.3
Emotional posts (where users decribes his emotional condition)	42.9	28.6*	51.9*	36.7	53.2
Posts with users opinion on significant events or things	31.0	24.5	35.1	31.6	29.8
Educational posts	22.2	16.3	26.0	20.3	25.5
The posts in which users try to show themselves or their friends with the best hand or to show the result they has attained	18.3	6.1*	26*	17.7	19.1
Posts containing statistical information (surveys, scientific results)	16.7	22.4	13.0	15.2	19.1
Advertisement posts	14.3	14.3	14.3	8.9*	23.4*
Motivation posts, which contains a call for action (to open business, earn a million, become well-known)	12.7	10.2	14.3	15.2	8.5
Positions in which there is a statement of injustice	12.7	10.2	14.3	12.7	12.8
Marketing posts, which in addition to advertising of the product/service different marketing techniques are used	3.2	2.0	3.9	5.1	0

moral self-improvement; professional competencies and skills development; friendship strengthening; fun, entertainment; civil self-determination.

The analysis shows that the most important needs of all subgroups are strong family, health and love; civil self-determination is in the last place. There are differences between the needs of those, who has higher education, and those, who is still studying. Friendship strengthening (p = 0.001), fun and entertainment (p < 0.02) is more important for students, while people with higher education consider love to be most significant (p < 0.04).

The needs vary in different types of posts. Motivational posts, appealing for action (e.g. to open your business, earn a million, become famous) publish people with less need for civilian self-determination (p = 0.001) and self-realization (p < 0.04).

Emotional posts, which display users' mood/sadness/joy/excitement/love are typically published by people with expressed need for love (p = 0.004). People with a certain need for fun and entertainment (p = 0.05) tend to publish posts with advertising information about a product (or service).

Marketing posts, which, besides advertising of the product (or service), also contain dead-lines and other marketing techniques, are likely to publish users with major need for strong family ($p = 0.001$), and less intense need for fun and entertainment ($p = 0.001$).

People with less need for strong family ($p < 0.02$) and more intense need for friendship strengthening ($p < 0.05$), as well as spiritual and moral self-improvement ($p < 0.05$) tend to publish posts with their own reflections on important events or things. Entertainment posts (humor, jokes, fables) are usually published by people with an expressed need for fun and entertainment ($p = 0.001$).

Analysis of the first survey results, as well as, both respondents and experts' comments, who rated the posts, allowed to develop advanced 2-level classification of posts. This classification is not only easier to perceive, but it also helps the experts to formulate more precise classification criteria, which increases the consistency of the provided assessments:

1. Informational Post:
   - 1.1 formal/statistical;
   - 1.2 eventual;
   - 1.3 personal;
   - 1.4 intellectual and reflectional/quotational;
   - 1.5 referential (web address only);
   - 1.6 cooking related posts;
2. Emotional Post:
   - 2.1 positive;
   - 2.2 negative;
   - 2.3 congratulatory;
3. Motivating Post:
   - 3.1 charitable;
   - 3.2 marketing;
   - 3.3 action incentive.

During the second (additional) pilot survey it was revealed that the average number of a respondent's posts for six-month period amounted to 36.9 (minimum —1, maximum—318).

That is, the social network user of a certain age publishes 1 post in 5 days on average. Considering the average posting frequency and the amount of deviation in a specific period of time, one can reasonably assume, whether there are any events or life changes relevant for the respondent in a particular period.

While rating the posts, it was taken into account that the same publication could be informative, emotional and motivating simultaneously. For example, the post: "I'm in the best dance school! Each lesson gives me a lot of positive emotions! After the class I am happy and inspired! Tomorrow there will be a master class in our school. Welcome! Treat yourself with the moments of joy and lift your spirit!", —can be assigned to these three categories: informational, emotional (positive), and motivating (action incentive).

There can be divided other classes and subclasses of posts (according to the percentage of all published posts; a range from minimum to maximum is represented in brackets):

- Informational—41.6 (0–100);
- Emotional—27.1 (0–100):
  - Positive—20.7 (0–100),
  - Negative—3.9 (0–33);
- Motivating—10.2 (0–100):
  - Charitable—0.6 (0–20),
  - Marketing—1.8 (0–33),
  - action incentive—7.9 (0–100).

The following non-text posts were taken into account:

- Photo—73.1 (11–100);
- Audio—13.1 (0–71);
- Video—10.7 (0–100).

Obviously, informational posts are published more often than other types. Despite the apparent saturation of social networks with pessimistic emotions, the analysis shows that negative posts represents less than 4 %, the maximum number of negative posts does not exceed one-third of all publications.

On one hand, this observation illustrates a more cautious attitude to so-called "expert assessments" of the blogosphere state; and on the other hand, it highlights that the effect of negative content could be much more visible than it's relative share of total information.

Some gender predisposition in relation to posts was revealed: women prefer to publish personal, emotional, positive and audio posts.

4 Conclusion

Information technologies are increasingly penetrating into everyday life. It lead to the fact that the Internet and social networks become a new communication medium. From some points of view these forms of communication are claimed to be a new form of reality (so-called virtual reality, online reality in contrast to the usual offline reality). The research has shown that the analysis of the content that is stored on the user's personal account in the social network can present a lot of information about the personal characteristics, preferences, value orientations of the user. One of the main results of this research is the identifying the relationship between categories of posts and demands of the users, who publish these posts. Thus, social networks can be used by the researches as new tools for the analysis of the user's identity.

The conducted research provides tools for the specialists who are working with young people with new tools for assessing and monitoring the mood and emotional state of young people. On the other hand, these results can be used in the field of information security, as it becomes possible to construct user's vulnerabilities profile without disturbing user because of using user's digital traces in the social networks. The dynamics of the emotional change of social network users may be obtained through tracking posts in some groups or communities in social networks. What is more, it can also improve the national security in case of the tracking informational posts that contains dangerous or harmful content.

Currently, the analysis of published posts is being produced by the experts. But, at the same time, the classification and criteria for the assignment of a post to a particular class has been already developed. So it becomes possible to automate this stage of processing available data, and therefore will enable professionals involved in psychological counseling, to work with youth in "one-click" [1, 2, 4, 6].

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Bayesian Optimization of Spiking Neural Network Parameters to Solving the Time Series Classification Task

Alexey Chernyshev

Abstract This study contains the application of spiking neural networks to time series classification task. Because of the lack of mathematical framework for such biologically inspired neural networks, this study tries to solve hyperparameter optimization task with the help of surrogate models. To define classification task quality metric that measures separability index based on Fisher's discriminant ratio is used.

Keywords Spiking neural network · Bayesian optimization · Time series classification

1 Introduction

Significant amount of studies is devoted to the classification of time series [1, 2]. Neural networks are known as universal approximators of the nonlinear functions $f(x)$ [3]. In the context of time series, it means that continuous time series should be replaced with discrete, window function should be applied, and the task should be brought to the approximation algorithm of the function $f(x(t_{n-k}),\ldots,x(t_{n-1}),x(t_n))$ where k is the size of the window.

The neural networks with internal state look promising. So-called reservoir computing that allows to approximate the dependence of form $f(x,t)$ [4, 5]. Such network is a dynamic system which is exposed to the disturbance of input time series $x(t)$. The dynamic of disturbed network creates a new time series $z(t)$, which contains some characteristic features of $x(t)$. Similarly to the classical approach, in this case we can define the function of classification quality. But it is only possible to formulate exact expressions for its gradient for the networks with simple dynamics.

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Depending on the model in use, the signal $z(t)$ can have different forms: continuous (Echo State Networks [4]) and pulsed (Liquid State Machines [5]). Pulsed form of signal in the context of neural networks is also called spiking to point out the connection with the biological neurons, for which this form of signal is typical.

This study focuses on the use of pulsed form of the signal as more biologically justified. This form also allows to use discrete event simulation where each pulsation is an event. Such model allows to perform large-scale simulations with millions of interneuron connections, using only personal computer.

In this paper we examined spiking computing reservoir. Its neuron weights undergo dynamics of spike-timing dependent plasticity, which is a biologically inspired rule of unsupervised learning [6]. The network dynamic, as well as learning rule, is set by a number of parameters. Output network activity is evaluated by the quality function of time series classes separation, the base of which is Fisher's ratio [7].

The search of the optimal network parameters demands a lot of computing expenses. In this paper we use the technique of search of global maximum with the help of Bayesian optimization framework based on surrogate models [8].

2 Task Description

We will examine the high-dimensional time series $x(t) \in \mathbb{R}^n$, which describes the state of the system in the moment of time $t \in [0, T]$ where T is the interval of system activity. The set of system states in which it can be in the definite non-crossing time intervals is set as $y \in y_j,\, j \in 1 : l$. To classify $x(t)$ means to define the system state in the moment of time t based on its previous states.

As a neural network model we examine recurrent network of SRM neurons [9]. Their weights are exposed to spike-timing dependent plasticity dynamics [6]. The membrane potential of i neuron $u_i(t)$ is configured by sigmoid activation function which sets the intensity of inhomogeneous Poisson process:

$$r_i(u_i(t)) = \frac{1}{1 + e^{-s(u_i(t) - \upsilon)}}. \tag{1}$$

Here s, υ are the parameters which define the function properties: the speed of function increase and the threshold activity accordingly. By reaching the threshold, the function changes the increase to decrease.

The neurons' population is divided into two layers: input layer that contains n neurons and generates impulses according to the input patterns; hidden layer, the dynamics of which are exposed to the disturbance of the input impulses, which causes new time series $z(t) \in \mathbb{R}^m$ where m is the quantity of neurons in the hidden layer.

The disturbance from neuron to neuron is transmitted by the synaptic connection, the dynamics of which are described by differential equation

$$\frac{s_j(t)}{dt} = -\frac{s_j(t)}{\tau_s} + aS_i(t). \tag{2}$$

Here τ_s is a time constant that defines the speed of signal fading on synapse; $S_i = \sum_j \delta(t - t_j^s)$, $t_j^s \in \{t_1^s, t_2^s, \ldots, t_k^s\}$ is a realization of Poisson process with intensity r_i (1) where $\delta(t)$ is a delta function (Dirac function); a is a constant that equals 1.0 for the excitatory synapse and -1.0 for the inhibitory. Every neuron summarizes the signals from the synapses that are connected to it.

The probability of connection between neurons is set for every layer with parameters: P_{12}—probability of joining by the excitatory neuron connection from the first layer to the neuron from the second one; P_{22}—probability of connection by the inhibitory connection of the two neurons from the second layer.

3 Model Optimization

There are several metrics for the analysis of the pulsed signals [10]. Kernel analysis techniques are based on the kernel that describes the level of similarity of two spike trains which are smoothed by low-pass filter. There are such metrics that work directly with pulsed signal, although smoothing creates bigger flexibility in kernels combination and allows to use well-studied pattern analyses techniques. The signal smoothing can be realized by its convolution with smoothing filter

$$\kappa(t) = e^{-\frac{t}{\tau}}, \tag{3}$$

where τ as a time constant of smoothing filter which is chosen in consistency with typical synapse dynamic. In this study this constant equals 15 ms. Thus, the output signal looks like

$$Z(t) = \int z(t')\kappa(t - t')dt'. \tag{4}$$

Let the input time series $x(t)$ correspond to k of examined system state switches. Then output signal $Z(t)$ can be represented as a positive definite matrix K (Gram matrix) of the $k \times k$ size. The matrix element K_{ij} is a real number that lies in the range [0, 1] and characterizes the level of similarity of time series parts that correspond to the system states y_i, y_j. This matrix can be built applying kernel pattern analyses techniques, using, for example, scalar product kernel

$$K_{ij} = \int_{t_0}^{t_1} \frac{Z^i(t)Z^j(t)}{|Z^i(t)|\,|Z^j(t)|}dt, \tag{5}$$

where $Z^i(t), Z^j(t)$ are parts of time series that correspond to the system being in states y_i, y_j. By getting the Gram matrix, it is possible to apply the various pattern analysis techniques [11].

Fisher's ratio is used as a metric quality that defines the quality of class separation of the system

$$F = \frac{tr(S_B^K)}{tr(S_W^K)}, \tag{6}$$

where S_B^K, S_W^K are between and within class covariance matrices accordingly, that are derived from [12].

4 Numerical Experiment

The set of initial data. The set of data is generated artificially: for 100 input neurons and every state class the intensities of Poisson distribution were obtained by realization of beta distribution with parameters $\alpha = 0.2$, $\beta = 0.9$. Poisson process was realized once for every class with duration of 500 ms. Each pattern was repeated the same amount of time for each class until reaching the duration limit of 60 s. Testing data set, which was used to evaluate the network quality, was formed by the same patterns.

Varying parameters. Using empirical knowledge, the parameters that influence the network dynamics the most were chosen (see Table 1):

- start weights' value of excitatory W_{12} and inhibitory W_{22} synapses for input and recurrent connections accordingly.
- values of τ_-, τ_+ that set the upper and lower window limits accordingly and characterize spike-timing plasticity.
- R_{ltp} the ratio of long-term potentiation (LTP) and long-term depression (LTD) (A_+, A_- in papers [13, 14]).
- S—the speed of activation function growth (1).
- τ_s—synaptic time constant (2).

Frozen parameters. Probability of neuron connections P_{12}, P_{22} were frozen during all simulations and equaled 0.5 and 0.25 accordingly. The learning rate was taken 10^{-3}, and each simulation contained five epochs.

Table 1 Parameters summary

	τ_+	τ_-	R_{ltp}	W_{12}	W_{22}	s	τ_s
Min	10.0	10.0	0.01	0.05	0.0	0.1	1.0
Max	400.0	1000.0	15.0	20.0	20.0	10.0	1000.0

Surrogate model. We made a sample of 1000 values of varying parameters in Latin hypercube, built surrogate model and estimated system learning quality. The results were randomly divided into cross validation sets by 10 folds. The data was processed by regression model based on Gaussian process with mean square loss function. The minimum of loss function for Gaussian process for covariation function Matérn 1/2 is reached with automatic relevance determination (ARD).

Software. The author's library[1] was used for the dynamic neural networks realization. The GPyOpt library[2] was used for optimization based on surrogate models.

5 Results

The parameter optimization process was launched three times. Table 2 shows the value of found optimal parameters. The last line in the table shows mean value of automatic relevance, the value of which shows the parameter's influence degree on the system's quality (the bigger the number, the less the parameter's influence).

The results show that value of recurrent inhibitory weight is the most influential on the classification quality. Its optimal value is relatively stable among all the experiments. The recurrent inhibitory network presence makes the network neurons compete for the opportunity to generate the signal. This dynamics makes neuron signals decorrelate with each other, which leads the covariance matrix of $Z(t)$ to approach the identity matrix. This influence on the output signal encourages various network signals to respond to various features of the input signal. This is the form of sparse coding which is often used in the machine learning algorithms (FastICA [15], Slow Feature Analysis [16]).

The speed of activation function growth has also shown itself as one of the parameters that influences the classification quality. The high values of this parameter make the stochastic system give more stable results, although the complete lack of stochastics limits the weights' space exploration with spike-timing dependent plasticity.

It is curious that parameters τ_+, R_{ltp}, τ_s take different values for optima without a big influence on the classification quality. It can be explained by the presence of dependence between these parameters, and this subject demands further research.

Figure 1 shows a parameter surface cutoff close to optimal parameter value W_{22}. Here on X-axis is the normalized value of this parameter, and Y-axis is the logarithm of the system quality $log(F)$. The dashed line on the figure corresponds to surrogate model; the solid line—the experimental results.

[1]https://github.com/alexeyche/dnn.

[2]https://github.com/SheffieldML/GPyOpt.

Table 2 The optimal set of parameters

	τ_+	τ_-	R_{ltp}	W_{12}	W_{22}	s	τ_s	F
Run 1	341.0	987.3	2.4	9.4	14.6	9.8	368.2	1.11
Run 2	84.0	940.0	8.5	20.0	13.2	4.4	281.3	1.20
Run 3	10.0	1000.0	1.18	5.73	13.63	10.0	75.2	1.05
ARD	166.6	25.2	123.0	0.5	0.05	0.2	5.5	

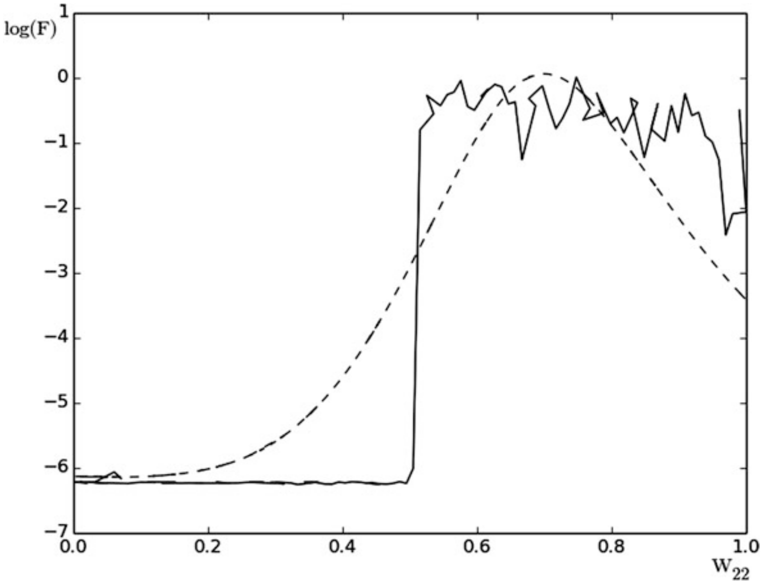

Fig. 1 Experimental and model values of W_{22}

6 Discussion

Combinatorial explosion of the various parameter combinations of the complex dynamic networks limits their use in real tasks. In this study the solution of this problem is attempted using surrogate model of classification quality criteria.

The further direction of the research requires thorough analyses of free parameters influence classification quality for more complex systems with near-chaotic dynamics that. As it assumed in paper [17], it carries important information about the structure of the analysed time series.

We can see in Fig. 1 how non-stationary resulting dataset is. It would be natural to use more advanced Bayesian optimization techniques like “Heteroscedastic Tree Bayesian Optimization” [18] for example.

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Simulation of Learning in Neuronal Culture

Alexey Degterev and Mikhail Burtsev

Abstract The neuronal cultures in vitro plated on the multielectrode arrays is an important object of research in modern neurosciences. The protocol of culture stimulation which allows to receive a required response of culture on a selected electrode in response to stimulation is known. Such stimulation protocol can be considered as the elementary form of learning. In this study we create model of neuronal culture in vitro and obtained primary data on ability of such model to learning through stimulation.

1 Introduction

Experimental studies of primary neuronal cultures in vitro show that dissociated neurons are able to self-organize in a network that demonstrate a learning like adaptation [1–4] in a closed loop stimulation protocol. But despite of an active research in the field of computational neurobiology [5–10] related to the simulation of neural networks in vitro there is no computer model of learning in neuronal cultures. There are a variety of simulations with (1) a number of neurons varying from 100 in [9, 10] to 5000 in [5, 6], (2) various models of connections between

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neurons such as random connections with random delays [5, 6], scale-free networks [8] and small-world networks [8–10], (3) a presence [8–10] or absence [5–7] of a long-term synaptic plasticity in a model. In our model we tried to unite as many factors which characterize the properties of the neuronal culture in vitro as possible, at the same time keeping the model as simple as possible to ensure computationally feasibility. The resulting architecture simulates a network consisting of 5000 neurons located on the flat space with the preference of short links between neurons and long-term synaptic plasticity. We studied the potential of the model to reproduce learning in vitro according to the stimulation protocol proposed in [1].

2 Materials and Methods

The model was implemented using the NEST library [11]. Simulated network consisted of 5000 Izhikevich neurons. Values of parameters for excitatory (70 % [5]) and inhibitory (30 % [5]) neurons were taken from [12]. Spatial distribution of neurons was defined in agreement with dimensions of the microelectrode array (3 × 3 mm) [13]. The probability of connection between two randomly chosen neurons was inversely proportional to the distance between them $\mathrm{P}(r) = \mathrm{e}^{-\mathrm{A}r}$, where r is a distance between the neurons in millimeters, A is a constant. With a different choices of the coefficient A it is possible to obtain a network architecture in which neurons are generally connected with the closest neighbors and have only a few long links [14, 15]. In our simulations A = 4. Closed loop stimulation was applied to the network according to the learning protocol [1].

3 Results

At the first stage we have studied the difference in the behavior of the network bursting activity in response to the stimulation pulses of 1 ms with the “small” and “large” electrodes affecting $\sim$10 and $\sim$40 neurons respectively. As expected the stimulation via “large” electrode was more effective. Figure 1a shows the average response of the neuronal culture model to the stimulation. Not each stimulus caused an activity therefore the median profile of activity is close to zero. At the same time 75th percentile gives an approximate profile of the evoked population activity bursts.

Figure 1b shows an evolution of neuronal network responses to continuous stimulation via the single “large” electrode with a 5 s period. Not each stimulus causes a population activity burst. This might be due to the transient network wide weakening of the weights after the population burst. Only in 26 % of cases

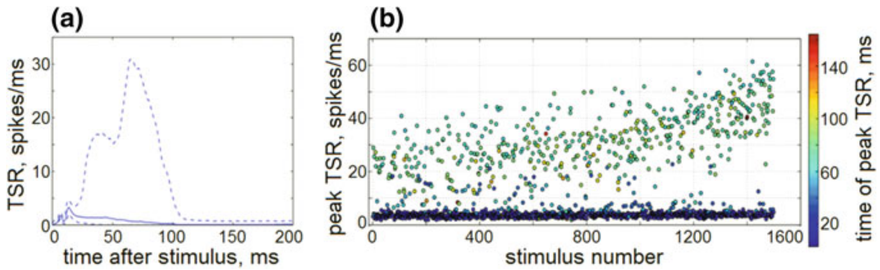

Fig. 1 **a** An averaged total spike rate (TSR) of the simulated neuronal culture in response to 1500 stimuli. The *solid line* is the median, *dashed lines* are 25 and 75 *percentiles*. **b** Evolution of the model response to the stimulation. The peak amplitude of the response to stimulus in 200 ms post stimulus is shown, and a delay of the response peak is indicated by color

stimulation evokes a burst with peak amplitude more than 20 spikes/ms. Out of 60 simulated electrodes only 6 were able to produce population bursts.

It is necessary to satisfy an important preliminary condition to implement the learning protocol. In the initial experiment [1] the electrode records activity only of the closest neurons however in our simulation the electrode detects activity of 40 neurons on the average. Therefore it is necessary to define a threshold value of activity which will be considered as the event on the recording electrode. To estimate this threshold 300 consecutive stimuli were applied to the stimulation electrode and the amount of spikes on all other electrodes in a time window (40, 60) ms after the stimulus was calculated. We tested a range of threshold values from 1 to 25 in a series of runs and chose the value of 10 spikes as the most suitable because it results in 13.5 % of cases where stimulation lead to event detection. 80 % of all the responses to stimulation evoked activity with amplitude less than 5 spikes which is similar to background spontaneous activity.

To choose a target electrode for learning 15 stimuli were applied, and for all electrodes response to stimulus ratio (R/S) was calculated. The electrode which had responded only once or did not at all to a series of 15 consecutive stimuli was selected $(R/S \leq 1/15)$. In the original protocol [1] $R/S \leq 1/10$. Other parameters of the learning protocol remained the same: (1) the stimulation rate was 1 Hz, (2) the training phase lasted at most till 10 min (600 stimuli), (3) the resting phase was lasting for 5 min.

Top panels on Fig. 2a–b show successful learning curves for a particular target electrode. After 20–40 learning trials, the desirable predefined response of at least 2 events in a series of 15 consecutive stimuli on the target electrode recurrently appears within no more than 20 s (20 stimuli). At the same time required response was not attained when any other electrode was selected as a target one. Bottom panels on Fig. 2 show learning curves for the cases when the learning failed.

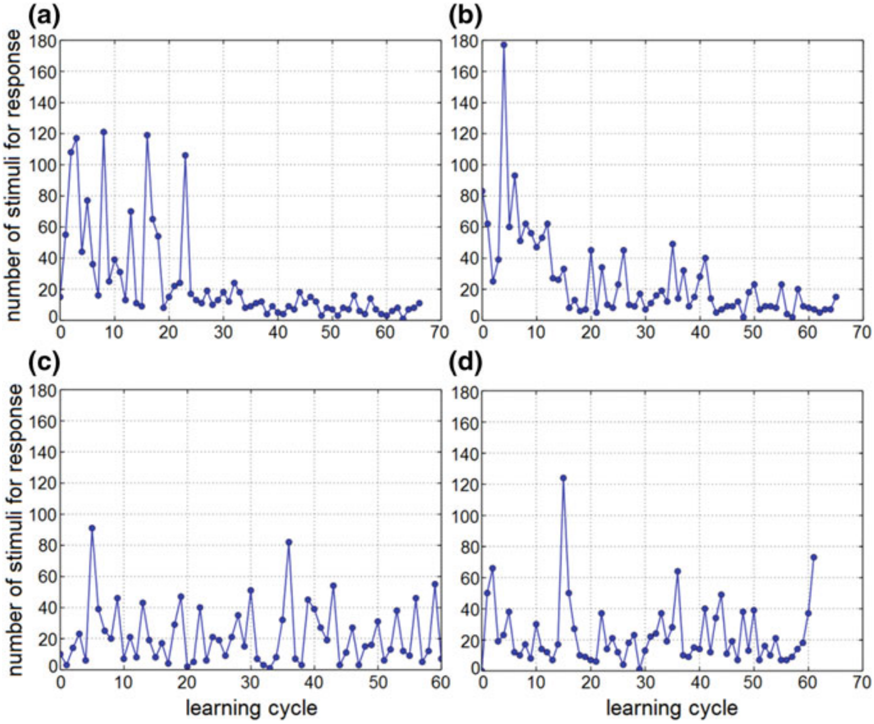

Fig. 2 Typical learning curves of the simulated neuronal culture. **a**–**b** Learning was successful. **c**–**d** Learning failed to produce required response

4 Discussion

The main goal of our study was the development of a simple but biologically plausible computer model of learning in neuronal culture. The direct application of the established experimental protocol [1] without any modifications produced no results. Recorded spontaneous background activity of the simulated network was higher than in experiments in vitro and definition of a target electrode as an electrode with a low probability of spiking in some time window after the stimulus cannot be applied. As a result to detect a deviation in the activity of the network from the background the threshold was introduced.

The next problem was a poor response of the model to the stimulation. To combat this issue we studied a number of model variations. Namely, (1) stimulation of the network through a "small" electrode affecting about 10 nearby neurons, (2) "large" electrodes affecting about 40 nearby neurons, and also (3) stimulation through a pair of neighbors electrodes. The "large" electrode model was found to give a higher probability to evoke a population burst. Yet, the stimulation of only 6 out of 60 electrodes produced population response. Even for these electrodes a probability of burst initiation was about 26 %.

In all experiments with the model only one pair of stimulating and target electrodes that can demonstrate learning was identified. The effect was confirmed in 8 independent learning experiments with this pair of electrodes. All this experiments demonstrated successful learning. In every case learning curve was different but quickly converged to the expected low values (Fig. 2a–b).

Our study is the first that qualitatively reproduced experimental results of in vitro neuronal culture learning [1–3] in computer simulation.

In spite the fact that proposed model was able to demonstrate learning in a simulated neural network this learning was reproduced only for the one pair of stimulating and target electrodes. This might be caused by non-optimal distribution of weights in the network at the beginning of learning. On the next stage of our study we plan to extend the pre-training period of spontaneous network activity to obtain "mature" distribution of weights. This should increase the probability of the response to the stimulation and make easier to find a target electrode for learning. It is also important to investigate how potential of the simulated neural network to learn depends on the rate of synaptic changes defined by parameter λ in the STDP model [16].

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Biologically Plausible Saliency Detection Model

Natalia Efremova and Sergey Tarasenko

Abstract We propose a novel neural network architecture for visual saliency detections, which utilizes neurophysiologically plausible mechanisms for extraction of salient regions. The model has been significantly inspired by recent findings from neurophysiology and aimed to simulate the bottom-up processes of human selective attention. Two types of features were analyzed: color and direction of maximum variance. The mechanism we employ for processing these features is PCA, implemented by means of normalized Hebbian learning and the waves of spikes. To evaluate performance of our model we have conducted psychological experiment. Comparison of simulation results with those of experiment indicates good performance of our model.

Keywords Neural network models · Visual saliency detection · Normalized hebbian learning · Oja's rule · Psychological experiment

A precise processing of only important regions of visual scenes is one of essential properties of human visual system. Extraction of important regions is referred to as *selective attention*. To date, two types of attention have been distinguished: bottom-up and top-down. Bottom-up attention is believed to be triggered only by characteristics of the visual scene. Bottom-up selective attention is also referred to as *saliency*.

In this paper, we introduce an unsupervised neural architecture, which detects the salient regions in visual scenes in neurophysiologically plausible way on the one hand, and in the computationally inexpensive manner on the other hand. To achieve these goals, we use three main neurophysiological findings which comprise a neurophysiological plausibility of our model: (1) findings by Knierim and Van Essen [1]; (2) waves of spikes [2]; and (3) normalized Hebbian learning [3].

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Knierim and Van Essen [1] found that a neuron produced weaker response if the stimulus is the same within the stimuli of the surrounding neurons comparing to the case than stimuli of the surrounding neurons are different. Therefore a neuron with an input stimulus outstanding from the surrounding texture will produce higher response.

Concept of *waves of spikes* has been introduced by Van Rullen and Thorpe [2]. The core of this concept is that the stronger response is produced by a neuron faster than the weaker one. Therefore neurons fire with different speed. The responses of coherently firing neurons form waves of spikes.

We also utilize the principal component analysis (PCA) that was proven to be effective instrument for saliency detection [4]. We employ neurophysiologically plausible Oja's rule, which allows to extract the first principle component in a neurophysiologically plausible way [3].

1 Model Description

In this section, we describe in details each computational principle we employ, and the way how all three principles are integrated together to deliver simple neurophysiologically plausible mechanism of saliency detection.

Unfold Static Image in Time by using Waves of Spikes concept. An integrate-and-fire neuron integrates its inputs over time until it reaches a threshold, and fires a single spike (action potential). After a certain refractory period, neurons start functioning again. Therefore, the more a neuron is activated, the sooner it fires. This means that the latency of firing of a neuron will reflect the strength of its input. Therefore, if stimuli are presented to the population of neurons, the first spike of the population corresponds to the most activated neuron, the second spike to the next most activated neuron, etc. This idea is the basis of the *Rank Order Coding Scheme* [5].

The neurons, whose actual visual input is closer to the preferred stimulus, fire faster [2]. Therefore, the higher is the activation of neuron the faster it fires. In [6] (p. 1518), the following approach for modelling such process by means of non-spiking neural networks was suggested: "…The neurons with unit activation (response is 1 on the normalized scale) fire first. Then the neurons with activation greater or equal to $1 - \epsilon$ $(\epsilon = 0.1)$, excluding previously fired neurons, will fire and so on. Thus, the neurons with the same activation level form 'waves of spikes'. Consequently, the original retinal image is unfolded in a time domain."

In the case of color intensity, we consider that spikes corresponding to the higher color intensities are produced faster than spikes corresponding to the lower color intensities. Thus, the highest color intensity (unit amplitude on the normalized scale) spikes will be generated.

To employ the concept of *waves of spikes* in this study, we consider color RGB image as three independent R-, G-, and B-channels. Then we decompose signal of each channel into 10 intensity levels starting from 0 with step ϵ. Thus, the first level contains color intensities from the interval [0, 0.1), second level contains intensities from the interval [0.1, 0.2), etc.

Therefore it is possible to decompose entire image into several layers (levels of intensities). In our study we use color images. For color images three separate color channels are used. Then intensity levels are applied to each of three color channels. After such decomposition, we split each intensity layer for each color channel into 16 × 16 pixels patches. Each 16 × 16 patch is considered to be a receptive field (RF) of a visual neuron, which extracts the first (main) principle component by means of Oja's rule.

PCA and Oja's rule. PCA was used by Zhou et al. [4] in conjunction with distance computation and histogramming methods to detect salient regions. PCA itself is not biologically plausible enough for our purposes. On the other hand, normalized Hebbian learning (Oja's rule) [3] is biologically plausible analogue of PCA. Oja's rule delivers the first principle component into weights of a given neuron tuned by such learning rule.

Oja's learning rule. Oja [3] has proposed normalized Hebbian or Oja's rule:

$$w(k+1) = w(k) + \mu(y(k)x(k) - y(k)^2 w(k)) \tag{1}$$

where y is output of the neuron, $w = (w_1, \ldots, w_n)$ is vector of synaptic weights, μ is a learning rate, and k indicates the iteration number.

The final weight vector after learning will represent the first (main) principle component of the presented data. We employ Oja's rule to evalute main principle component of the color intensity presented in each patch.

Identifying salient regions. In the work by Knierim and Van Essen [1], it was shown that neural responses depend on the activation of surrounding neurons. Therefore it is necessary to compare how similar the stimulus of the neuron at the

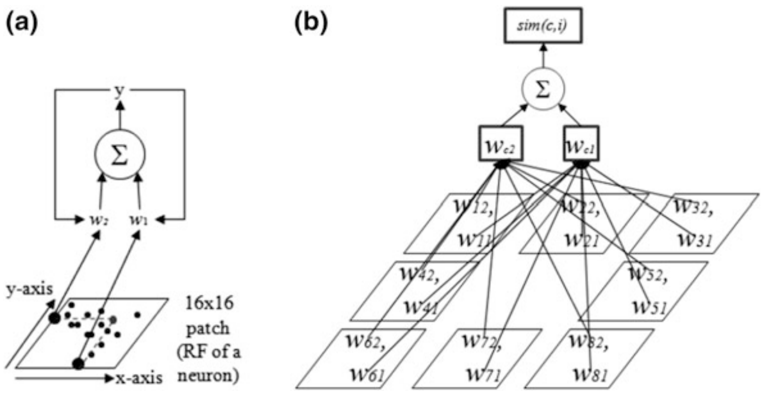


Fig. 1 **a** Stage 1: Oja's learning. Use x- and y-coordinates of the non-zeros intensity pixels to compute approximation of the first principle component for the non-zero intensity pixels within the given 16 × 16 patch **b** Stage 2: Lateral interaction for similarity computation

center is to the stimuli of the surrounding neurons. We consider that the contents of 16×16 pixel patches can be represented by their first principle components. Then the more similar the contents are the higher the value of the dot product of two first principle components.

This approach is implemented in two stages (Fig. 1). *Stage 1* is tuning the weight vector of each neuron to approximate the first principle component of the 16×16 pixel patch (RF of a neuron). Since all synaptic weight vectors are the first principle components, if the input is a synaptic weight of another neuron, then the output of the give neuron is a cosine of an angle between two principles components of two neurons. We consider the cosine of such angle to characterize the degree of similarity between two patches.

Therefore in *Stage 2* we compare similarity of stimuli of surrounding neurons by means of computing dot (inner) product between the weight vectors of the center neuron and the surrounding ones: $sim(c, i) = w_c^T w_i$, where w_c and w_i, $i = 1, \ldots, 8$, are weight vectors of the center neuron and the surrounding neurons after Stage 1. This similarity measure is computed for each pair of the center neurons with one of the surrounding neurons.

By computing similarity with surrounding neurons, we estimate how homogeneous the vicinity of the given center neuron. We set the decision rule to distinguish between similar and dissimilar stimuli: if $w_c^T w_i < 0.1$, then we consider that contents in the RFs of the center neurons and *i*-th neuron are dissimilar.

To process a stimulus in the RF of a given neuron, we compute first principle component for each color channel for the given patch. Then we calculate the total number of dissimilar weight vectors in a surrounding neurons for each color channel separately. If the number of dissimilar weight vectors across all intensity level for a certain color channel is greater than a threshold (set to 10), we consider that given stimulus is a *salient region* for the given color channel.

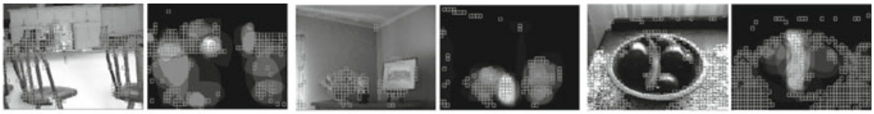
Finally, throughout the color channels, we calculate frequency of a certain patch to contain salient regions. At this point we cut off the patches with frequencies less than an expected value by chance. The expected value is calculated as a ratio of total number of patches containing salient region across color channels and intensity layers to the total number of patches to cover the figure.

2 Psychological Experiment

Method. *Objective*. In this study, we aim to show that our model can predict the location of salient regions in natural scenes and home scenes in the similar way human subjects do. To evaluate performance of our model, we have conducted a psychological experiment to collect the data about performance of human subjects.

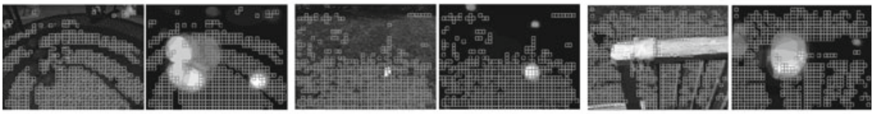
Participants. All participants were undergraduate students (ages $18 - 23$) at the Plekhanov's University, who received course credit for participation. All participants had normal or corrected-to-normal vision. In total 18 subjects were tested, including 11 males and 7 females.

Table 1 ROI maps and model performance: Part1

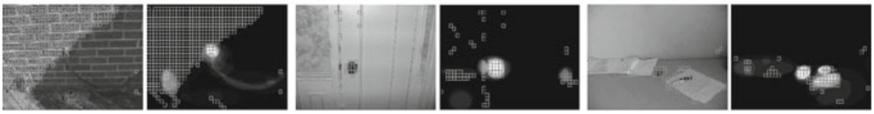


WP=0.944, WR=0.375 WP=0.938, WR=0.486 WP=0.827, WR=0.398

WP=0.967, WR=0.511 WP=0.774, WR=0.567 WP=0.701, WR=0.284



WP=0.486, WR=0.425 WP=0.360, WR=0.562 WP=0.419, WR=0.404



WP=0.537, WR=0.460 WP=0.734, WR=0.411 WP=0.982, WR=0.472

Procedure. During the experiments, we asked participants to select all the regions, which attracts their attention on the given set of images. All the subjects were given the instructions to select all the regions of the image that attract their attention. They were asked to do it by using mouse to encompass the Region Of Interest (ROI) with a color curve on computer screen. Each ROI was defined as an area within the mouse selection.

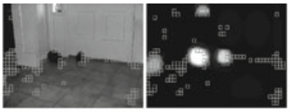
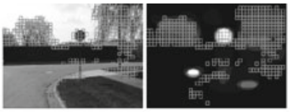
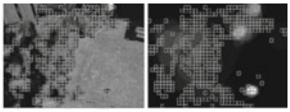
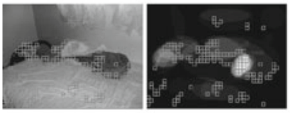
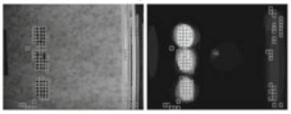
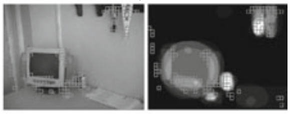
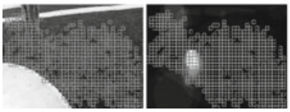
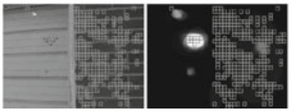
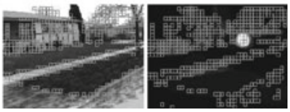
Results of Psychological Experiment. For the purpose of further analysis, we have discarded results of two subjects. One subject has not selected any region in either of images. The regions, selected by another subject, were too large for our purposes (over 30 % of a visual scene). We have also discarded some results of other participants for the same reason.

Finally, there are 12–16 individual ROI maps for each image. Integrated ROI map is obtained by superimposing ROI maps for a single image produced by all subjects. Integrated ROI map shows frequencies of selection of specified ROIs. The original images and corresponding ROI maps are presented in Tables 1 and 2.

3 Evaluation of the Proposed Model

To evaluate performance of our proposed model, simulation results produced by our model were compared with those of the human subjects.

Table 2 ROI maps and model performance: Part 2

		
WP=0.617, WR=0.339	WP=0.887, WR=0.599	WP=0.887, WR=0.478
		
WP=0.898, WR=0.273	WP=0.970, WR=0.451	WP=0.949, WR=0.273
		
WP=0.764, WR=0.556	WP=0.864, WR=0.379	WP=0.715, WR=0.508

The integrated ROI maps are frequency maps that illustrate how many participants have selected particular regions. Therefore the regions, selected by the majority of subjects (with high frequencies) can be considered more important than others. Therefore, detection of more frequently selected regions demonstrates better model performance than detection of less frequent ones. To take frequency of regions into account, we calculate *weighted precision (WP)* and *weighted recall (WR)* to evaluate performance of our model. By normalizing the integrated ROI maps, we obtain probability density of region selections. Therefore, the sum of all non-zero values should equal to 1. This probability distribution represents all positive samples and is used to compute WP and WR. The resulting WP and WR are presented in Tables 1 and 2. A comparison of average precision (0.734) and recall (0.327) versus average WP (0.772) and WR(0.439) illustrates that on average our model selects frequent salient regions. Overall results suggest that our model is quite accurate at predicting human judgements of ROIs.

4 Discussion and Conclusion

We proposed a neurophysiologically plausible saliency detection model. The main feature of our model is its unsupervised manner. The computational principles are considered to be employed by the human brain. Finally, our model demonstrates good performance of saliency detection based on only local information and is less computationally greedy than other proposed algorithms.

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Active Adaptation of Expert-Based Suggestions in Ladieswear Recommender System LookBooksClub via Reinforcement Learning

Nikita Golubtsov, Daniel Galper and Andrey Filchenkov

Abstract Fashion recommendation is one of the developing fields in e-commerce. Many different types of recommender systems exist with their own advantages and disadvantages. In this paper we create a recommender system for ladieswear that utilizes all recommender system approaches: collaborative filtering, content-based, demographic-based and knowledge-based. Using stylists' suggestions, we created distance space for items, user clusters and connected item features to users' characteristics. Stylist initial ratings were used to solve the cold-start problem. We adopted the Upper Conditional Bounds (UCB) algorithm for active selection of items which should be suggested. The system was designed with strong constraints dictated by the business process. The system worked for one month and estimated with 64 % of "likes" received for its suggestions, while the well-known Rocket Retail system shows only 55 % of "likes" after five years of its use.

Keywords Recommender system · Active learning · Reinforcement learning · Hybrid intelligent system · Fashion recommendation · E-commerce

1 Introduction

Recommender systems (RS) are intelligent systems providing suggestions for items expected to be of the user's most interest [9]. Application domain for RS is extremely wide: nowadays they are a necessary part of any e-commerce system. RS are used in websites such as imbd.com or kinopoisk.ru for film recommendation based on users' rates assigned to movies. The similar system is used by websites

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such as Last.FM, but for artist, albums and songs. Video RS are used in YouTube, RuTube and most of other websites hosting videos. Some websites such as tastekid.com and imhonet.ru have multiply areas of recommendations (movies, songs, books, etc.). Social networks such as Facebook or Vk.com use RS to suggest friends to users. Even search engines such as Google or Yandex are transforming into systems whose functionality is getting very close to RS.

Nevertheless, the main domain of RS application is e-commerce. It is well-known, that RS are useful tools for sales increase [10]. From giants such as Amazon to local web-stores, almost every seller uses RS to increase sell rates. The marketing agency Monetate has found that RS implementation helps to increase income in 4 times, conversion in 2.5 times and mean order value in 1.5 times [8].

LookBooksClub is a startup which is focusing on sending suggestions of ladieswear. The startup is not a seller and its profit is accumulated by successfully redirecting sales to partners, which are 20 online fashion shops, such as Lamoda, Wildberries, KupiVip and Butik. The ladieswear is chosen because it shares 67 % of cloth market in Russia [7] and there is a reasonable doubt on possible effectiveness and profitability on making suggestions to men since their consumer strategies may be different.

Previously, LookBooksClub business model was as follows. LookBooksClub has contracts with professional stylists (experts), who were producing personal suggestion to female client. In order to receive personal suggestion, a female client had to pass a large online survey. After that an expert defined, what cloth should be recommended to her. Finally, these suggestions were sent to the client, and she could buy everything she liked with supported hyperlinks to the corresponding items in the online shop. The described business model had certain disadvantages: an expert cannot know each item in all the online shops; high number of questions prevents some clients from passing the survey; this system is in high dependence on experts.

In this paper we describe a hybrid intelligent system developed for LookBooksClub, which requires experts' labor only on the first stage to make initial suggestions. After that the system should adapt to the users' behavior. We use reinforcement learning to implement such adaptiveness.

2 Recommender Systems

The domain of RS includes an enormous number of techniques with their own advantages and disadvantages. Due to a large amount of papers and books are devoted to this topic, we will focus only on the methods which can be applied for the described situation. A comprehensive overview of all the modern directions of RS can be found in [6].

RS are usually divided into collaborative and content-based systems [1]. Sometimes knowledge-based RS are also added to this division [5]. In this work we will use the more detailed classification of RS by Burke [3], because it suggest the most fine-grained division which is important for explaining the hybrid RS [2]. According to Burke, all RS can be divided into collaborative filtering RS, content-based RS, demographic RS and knowledge-based RS. All of these types of RS suit to solve the problem in the described domain of this paper. We will briefly describe all these recommender systems.

Collaborative filtering is an approach for recommending items to users which is based on already known users' behavior towards the items. It is the most popular approach for recommender systems [12]. The main disadvantage of the collaborative filtering is the cold-start problem [11], which prevents the system to work efficiently when it a makes recommendation to a new user or about a new item. Content-based systems in this context are systems that use additional a priori information about items, which is not connected to users' behavior towards these items, to make suggestions. Demographic-based systems in this context are systems that use additional a priori information about users, which is not connected to their behavior towards items, to make suggestions. Knowledge-based systems uses a priori knowledge of the domain to make suggestions.

Reinforcement learning based strategies are widely applied in RS [4]. A solid review can be found in [14]. The main application of reinforcement learning is usually connected to choosing the next item to recommend to a user.

3 General Scheme of LookBooksClub System

In this small section we describe the requirements to the recommender system and its functionality. At first, the client should answer a number of questions within the online survey. This is the information we have about this client. Then for each client we should suggest several items once a week. The suggestions are formed as items with the highest value of a certain metric, which we describe in Sect. 5. After the client is registered in the system, once a week a new letter is composed and is sent to her. This letter contains images of suggested items, "like" and "dislike" buttons and hyperlinks to the items in the shop.

All the following solutions were determined by the constraints we had. These constraints are defined by the business process. They are

1. We have no more than one month to estimate the system performance.
2. We can make a survey on not more than 500 clients, since on this stage attracting each client has a price.
3. We must minimize experts' work since it is very costly and it cannot be scaled.

The described constraints define the logic of the model we created. All the information we have is structured by experts. Additionally, we have demographic-based information (surveys) and content-based information (item properties). Together with that, we need to tune the system according to the users' behavior. Thus, we can say that the discussed system is the hybrid of all the system types described in Sect. 2.

4 Domain Formalization

The basic idea we use is to imply knowledge-based similarity measures for users and for clients. Following the experts' suggestions, we decided to splits clients into clusters and build up a metric space on the clothes set. The system uses a function $L(u, i)$ which describes the "will" of the system to recommend item i to user u. Once this function is obtained, the only thing that the system should do is to find k items with highest values of $L(u_\zeta, i)$ to create recommendation for the user of interest u_ζ.

4.1 Clustering Clients

All clients are described with tree features mined from the survey. These features were suggested as the most important for client clustering. They may have the following values:

- color type: winter, spring, summer, fall;
- age range: younger than 25 y.o., from 25 to 40 y.o. and older than 40 y.o.;
- price range: less than 3000 Russian rubles, from 3000 to 10,000 Russian rubles; from 10,000 to 25,000 Russian rubles and more than 25,000 Russian rubles.

Color type determines a set of colors which correspond to this client. Age range will help to determine which brands suit to these clients. Finally, price range determines what is the most preferable price for the client. Thus, we have $4 \cdot 3 \cdot 4$ different combinations of the described features. Each combination is a cluster. After the client passes the survey, her cluster is defined and never changes. The number of clusters is almost 50, which is the maximal estimate of classes for a sample containing 500 objects.

We consider each cluster independently; we run 48 independent algorithms for evaluating new suggestions. Let $C = c_1, \ldots, c_{48}$ denote cluster set. Then, $L(u, i) = L(u\hat{a}\breve{\mathrm{A}}\acute{\mathrm{Z}}, i) \forall i, i' \in c, \forall i$. Let $L_c(i)$ denote value $L(u, i)$ for any $u \in c$.

4.2 Measuring Similarity for Clothes

As well as clients, clothes are also described with three features, namely color, price and brand. These features corresponds to the features with which the clients were described. Thus, if color corresponds to the user's (cluster) color type, we assign *col* equal to 1, otherwise to 0; if brand corresponds to the user's (cluster) age, we assign *brand* equals to 1, otherwise to 0: if price is in user's (cluster) price range, we assign *price* equals to 1, otherwise to 0.

Then we can build a distance space with *price*, *brand* and *color*. First, define an item value. According to experts' opinion, choosing price range is more important than choosing color and choosing color is more important than choosing brand. Thus, we can define item value as

$$v(i) = \frac{3 \cdot price + 2 \cdot color + brand}{6}.$$

After defining item value, we can simply define distance on the item space in the following way: $\rho_I(i, i') = |v(i) - v(i')|$.

5 Adaptive Strategy and Expert Suggestions

In the previous subsection we have defined very rigid user and item spaces: users are split into 48 clusters and item are projected on a one-dimensional space, and the distance between these projections is used to define distance between items.

5.1 General Idea of Adaptive Strategy

The system tries to maximize the number of "likes" given by users to the suggested clothes. Also the user can mark a cloth with "dislike" or not estimate it at all. Since we decided not to distinguish users from different clusters, we formalize the value being maximized for each cluster c in the following way:

$$r_c(i) = \frac{l_c(i) - d_c(i)}{n_c(i)},$$

where $l_c(i)$ is the number of likes that the users from c gave to the item i, $d_c(i)$ is the number of dislikes and $n_c(i)$ reflects how many times we have suggested the item i to users from c.

If we suggest that the experts have built the perfect model for users and we must trust its suggestions, then we can simply assign $L(u_\zeta, i)$ to be equal to $r_c(i)$, where $c : u_\zeta \in c$. But we cannot expect this representation to work well enough due to its simplicity and ignorance of many useful clients' and item features. However, these simplifications were necessary because of the constraints for experts' worktime. What is more important, the mapping which was suggested by the experts from client space into item space is based on the very naïve hypothesis: each client's feature strictly corresponds to a certain item feature.

To strengthen the system, we make it use its experience on correct and incorrect suggestions what to recommend. This can be done within the paradigm of reinforcement learning [13]. Reinforcement learning is a neuro-inspired approach which tried to reflect the way human's brain processes streams of information and which has to simultaneously learn and apply learnt knowledge.

In this paper we reduce the problem to the well-known multi-armed bandit problem. This problem is stated as follows: assume we have a set of random variables $(x_1, \ldots, x_n)$, with mean values $m_1, \ldots, m_n$. On each step we can choose a random variable and receive the reward which is equal to the variable value. The goal is to maximize the reward when nor x_i, neither m_i are known.

With the introduced notation the reward function is simply $r_c(i)$. Thus, we adopt the well-known UCB algorithm. The main idea of this algorithm is to pick variables according to a certain function which represents tradeoff between exploration (upper confidence bound) and exploitation (mean). In our term, we should assign $L(u_\zeta, i)$ to be equal to

$$r_c(i) + \sqrt{\frac{2 \ln n_c}{n_c(i)}},$$

where $u_\zeta \in c$ and n_c is the number of items suggested to all users in cluster c.

In the classical UCB we should try each variable (e.g. item) one time and then apply this strategy. However, this requires to suggest each item, which does not seem to be very productive. This problem is very similar to the "cold start" problem in recommender system. To avoid it, we use experts' suggestions.

5.2 *Adaptive Strategy for Hybrid System*

We ask experts to assign several (15–20) items for each cluster. These suggestions are considered as the "core" suggestions which will be extensively used during the system exploitation and which defines how should we explore the item space. Due to the fact that we have chosen only a small number of items, most of the items still have no additional information which can be used in the adopted UCB work. To handle that, we will use the introduced distance ρ. Thus, expert suggestions together with metric space will produce all initial value of mean reward. In this subsection we will describe the function $InEx(i)$ which assigns initial value for mean reward.

Let M_c denote the set of items chosen for cluster c by the experts. For items in this set we can assign a special value which will represent the initial trust to the experts. The higher is our trust to the experts, the higher the value we should assign. Thus, the system will assign higher priority to the items chosen by the experts in the first period of the system work. In this work we have picked the value of $InEx(i)$ for $i \in M_c$ equal to 10. This was based on nothing except our expectations on how many responses we will get and how trustable are the experts.

Though now we can pay higher priority to the items recommended by the experts, all the other items are still indistinguishable, and once the system has to choose what to suggest from the items, which were not suggested by the experts, it will find itself starting coldly. To avoid this, we will distinguish all the other items with respect to how close they are to the core items. Namely, for item i we can evaluate $\sum_{i' \in M_c} \rho_c(i, i')$. The item suits to the cluster: it is represented with $v(i)$. Thus, we can define the initial mean reward value for each items which does not belong to M_c:

$$InEx(i) = \frac{\sum\limits_{i' \in M_c} \rho_c(i, i') \cdot v(i\hat{a}\breve{\mathrm{A}}\acute{\mathrm{Z}})}{\sum\limits_{i' \in M_c} \rho_c(i, i')}.$$

The both described values are used as the initial mean reward for each item. Thus, the resulting adopted UBC algorithm tells us that we should assign $L(u_\zeta, i)$ to be equal to

$$InEx(i) + r_c(i) + \sqrt{\frac{2 \ln n_c}{n_c(i) + 1}}.$$

6 System Functionality and Comparison

It seems hard to find the proper methodology to estimate how well the system works, just because no reproducible experiment can exist. Another problem is that results of most of commercial systems are not publicly available.

We have run the system to work for one month and achieved the following results. We have accumulated 518 clients from one of our partner shops (we are not allowed to name it, therefore we will refer to it as “the shop”). We have sent 4 recommendation letters (one each week), each letter contained 4 suggestions on clothes. Thus, we have sent 2072 letters.

560 letters were opened. Thus, the open rate is 27 %. That means that 2240 suggestions were seen by the users. The users estimated 1297 of the suggested items which is 58 % of the seen items. 832 items received “like” (64 %) and 465 items received “dislike” (36 %).

Since the users were clients attracted from the online shop, we should compare the achieved results with Retail Rocket system that is used by this shop and which was described in Sect. 2. This data is not publicly available and was provided under cooperation with the shop form which the clients were attracted. The percentage of likes this system achieves is 55. This is less than 64. We also must note that the system Retail Rocket has been run for five years, while our system started with no knowledge on users’ behavior.

This allows us to state that the proposed approach helped to solve the cold start problem and show even higher performance than a more conservative system with incomparably huger knowledge of users’ behavior.

7 Conclusion and Future Work

In this paper we have presented a new approach to integrate expert estimations and adaptive reinforcement strategy to produce a novel hybrid recommender system. This system outperformed its analogue in asymmetrical conditions: the analogue has 5 years of history and the system started coldly. This means that this approach is beneficial and will be used in the Style & Go recommender system.

One of the biggest weaknesses of the described research is that so many heuristics where used without any theoretical consideration. This is the very consequence of the nature of the system that is a startup, which cannot focus on exploration much. The proposed adaptation of the UCB algorithm has shown high results within a single not well stated algorithm. We must remind that this experiment was constrained by the business logic, that is why we have to choose some parameters voluntary and simplify certain details. In this section we will discuss how the described approach can be generalized.

There are many ways to make the approach more complex and, thus, more flexible. The complexity of the approach defines two variables: what is the best performance the system can achieve and how much time does it take to achieve this performance. The more complex the model is, the higher performance can be achieved, but also the time increases dramatically. This is why we must always define what requirements the system has to met. In the described case we have very strong requirements: the system should show high performance in a very short time (one month). In general, the less time we have, the more the approach is expert-based. The more time we have, the more flexible adaptive strategy we may choose. This is very similar to the well-known bias-variance problem and a trade-off should be selected.

We plan to realize different improvements and see how well they work in comparison with the baseline. Also we are planning to suggest not only single items, but their combinations. The experts say that this can help to increase number of received likes because several clothes in combination provide support to each other. It is closer to the context-based RS.

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Visual Analytics Support for Carbon Nanotube Design Automation

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Abstract The nanoworld is invisible for a human eye. As a result, standard human methods for research and decision making are not applicable. Novel approaches are required in nanoengineering. In the paper, we present our approach to visual analytics support for carbon nanotube design automation. We illustrate our approach for research of thermal properties of single-walled carbon nanotubes. Features of our tool are discussed. Practical outcomes of our approach are outlined.

Keywords Visual analytics · Cognitive science · Carbon nanotube

1 Introduction

Biologically inspired cognitive architectures were proposed to emulate the complex process in human brain. Perception, learning, creativity, memory, and decision making could be emulated by different modules [1]. However, it is a challenge to manage the internal representation of the external world. The problem is much more complex for nanoengineering applications. The nanoworld is invisible for a human eye. In addition, a human being is unable to investigate the nanoworld using native haptic and auditory information channels. It hinders progress in nanoengineering.

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The problem can be overcome by novel approaches using cognitive methods [2, 3] and visual analytics.

Creativity is linked with evaluation and comparison [4]. However, it is difficult to compare two invisible objects. Currently, mathematical models of nanoobjects are used for evaluation of their properties [5, 6]. A designer obtains a big numerical data file that has to be analyzed. Then the best solution can be chosen.

In our approach, the compared objects are presented by their descriptors (i.e. multi-dimensional feature sets). A comparison of descriptors instead of invisible objects simplifies a decision making in nanoengineering. A designer can analyze the corresponding descriptors. It should be mentioned that our approach exploits the visual information channel only. However, the approach simplifies nanotube design flow in a comparison to the mentioned above mathematical approach because descriptors of nanoobjects are used. We apply our technique on real world data sets, namely for research of thermal properties of single-walled carbon nanotubes (CNTs).

The rest of the paper is structured as follows. The next section reviews the related works in the field of visual analytics methods application for carbon nanotubes thermal conductivity. Section 3 presents our approach for visual analytics support in nanoenegineering. We use single-walled CNTs as our test case. Finally, conclusions are derived in Sect. 4.

2 Related Works

The carbon film (graphene) and nanotubes are allotropes of carbon with unique transport properties [7, 8]. Nanotubes come in a variety of lengths L and diameters D. The distance between the adjacent carbon atoms in carbon nanotubes is equal to d_0 = 0.142 nm. Therefore, the atomic structure of a single-walled CNT is well described by a pair of indices (chiral indices), n and m. The diameter is calculated as follows:

$$D = \sqrt{m^2 + n^2 + m * n}\frac{\sqrt{3} * d_0}{\pi}. \quad (1)$$

The CNT thermal conductivity is dependent on the temperature, the nanotube length L and the average phonon mean free path l_0 [9]. In the case $l_0 > L$ the ballistic conduction mechanism is dominant. A quantum of thermal conductance is given as follows:

$$G_{th} = \frac{\pi^2 k_B^2 T}{3h} = 9.46 \times 10^{-13} T, \quad (2)$$

where
k_B is the Boltzmann constant;
T is the temperature;
h is the Planck's constant.

The thermal conductivity of nanotubes per unit length is calculated as follows:

$$G = G_{th} N_p, \tag{3}$$

where N_p is the number of phonon channels in a nanotube.

The number of phonon channels N_p is equal to the triple number of atoms in the unit cell $2N$, where N is calculated as follows:

$$N = \frac{2(n^2 + m^2 + nm)}{d_R}. \tag{4}$$

where d_R is equal to the greatest common divisor of the numbers $(2n + m)$ and $(n + 2m)$.

According to (3), (4) a single-walled CNT with the chiral indices (5, 5) and the diameter $D = 0.678$ nm contains 60 phonon channels and its thermal conductivity is given as follows:

$$G = 60\, G_{th}. \tag{5}$$

A single-walled CNT with the chiral indices (15, 15) and the diameter $D = 2.034$ nm contains 180 phonon channels and its thermal conductivity is given as follows:

$$G = 180\, G_{th}. \tag{6}$$

Table 1 summaries the data for the thermal conductivity of these nanotubes.

In [10] the tool for modeling of carbon nanotube thermal interface materials has been introduced. However, applications of visual analytics methods for CNT thermal properties analysis are not discussed.

Table 1 The thermal conductivity of nanotubes

	Indices		Temperature (K)		
	n	m	233	273	333
The thermal conductivity of the nanotube, G (W/K)	5	5	1.32×10^{-8}	1.54×10^{-8}	1.89×10^{-8}
The thermal conductivity of the nanotube, G (W/K)	15	15	3.96×10^{-8}	4.64×10^{-8}	5.67×10^{-8}

In [11] visual analytics approaches based on descriptors have been proposed. The approaches have been applied to real bioinformatics problems.

3 Approach and Software for Carbon Nanotubes Thermal Properties Analytics Support

In the paper, we introduce our novel approach to research of carbon nanotubes aimed to applications of visual analytics methods in nanoengineering. We propose to use descriptors of nanoobjects. Our descriptors represent objects by a set including visual images and numerical values. Data calculates according to (1)–(4). We use color-coding to provide data comparison in one single view. Colors for visualization of thermal properties are changed from red (the hottest region) to blue (the coldest region).

Our tool has been implemented using C# programming language and Microsoft Visual Studio 2010. We use the libraries of Tao Framework, including the OpenGL library. Figure 1 shows the class diagram of the developed software in UML notation.

Figures 2, 3, 4 and 5 demonstrate our software functionality. Figures 2, 3, 4 and 5 are shown the compared CNTs descriptors. The parameter G shows the calculated CNT thermal conductivity and the parameter *Diameter* shows the calculated CNT diameter. The parameters of each CNT (the chiral indices n, m) and the temperature T can be changed. The button *Draw* renews visual images and the parameters are recalculated according to the corresponding input values. Using an interactive visualization, the user can steer the analysis process more intuitively.

The active box *Draw info* shows the value of CNT sizes in the corresponding windows (Fig. 2). Figure 2, a shows 2 CNTs with the chiral indexes (5, 5) and (5, 0) and the temperature T is equal to 273 K. A difference between the armchair CNT (5, 5) and the zigzag CNT (5, 0) is obvious. Figure 2b shows 2 CNTs with the chiral indexes (5, 5) and (15, 15) and the temperature $T = 273$ K. It is obvious a difference for the CNT with larger chiral indices. The active box *Real scale* shows the CNT images accordingly to the CNT sizes (Fig. 2b).

Figures 3, 4 and 5 show the corresponding descriptors of numerical data given in Table 1. The thermal properties of the compared CNTs are obvious.

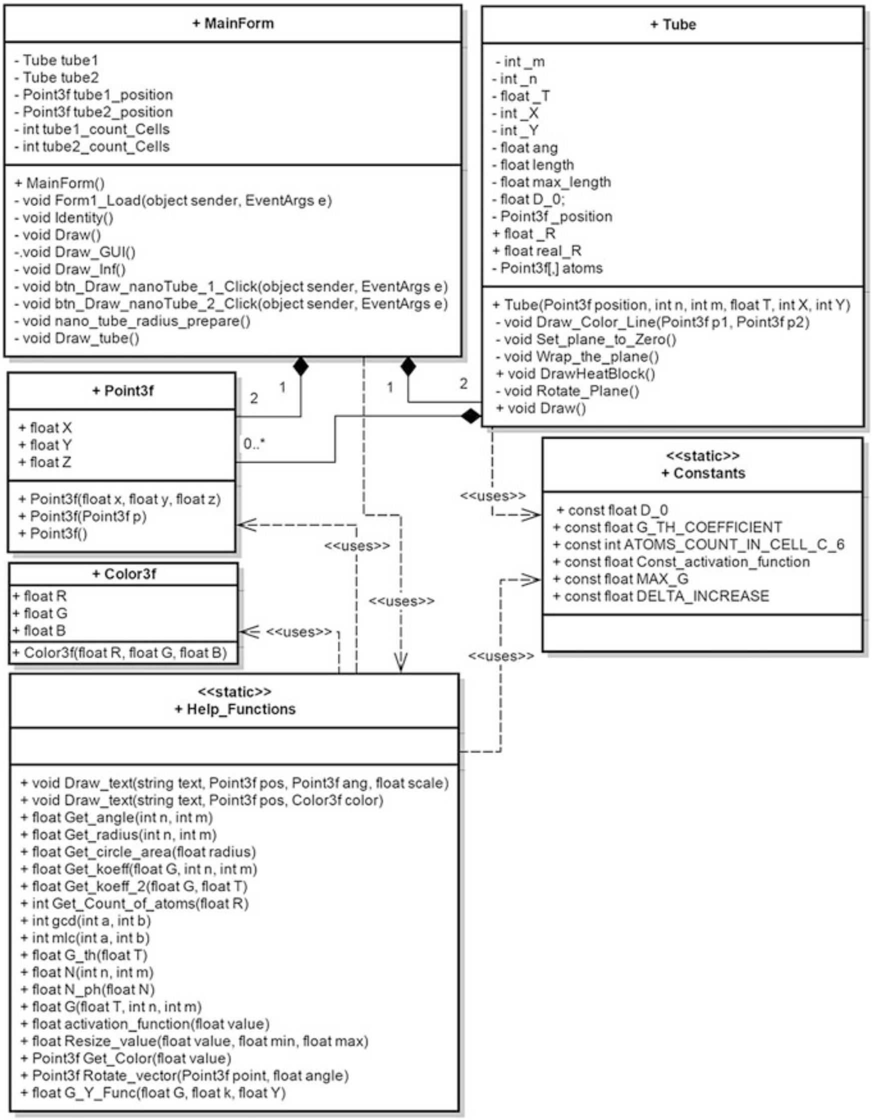


Fig. 1 Class diagram

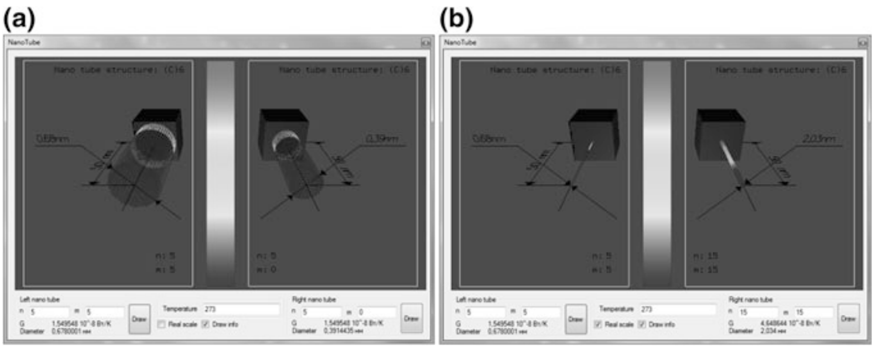


Fig. 2 **a** Visualization results for 2 CNT with chiral indices (5, 5) (*left*) and the chiral indices (5, 0), temperature $T = 273$ K. **b** Visualization results for 2 CNT with the chiral indices (5, 5) (*left*) and the chiral indices (15, 15), temperature $T = 273$ K

Fig. 3 Visualization results for 2 CNT with the chiral indices (5, 5) (*left*) and the chiral indices (15, 15), temperature $T = 233$ K

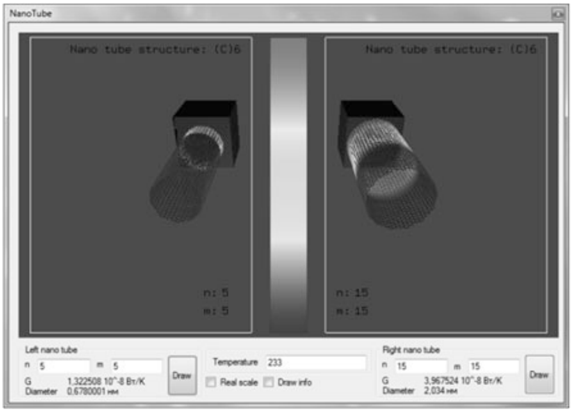
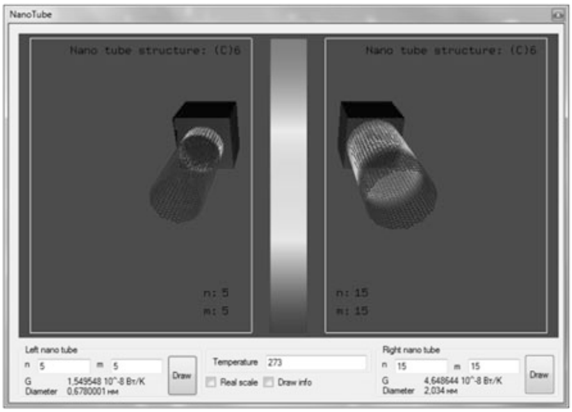


Fig. 4 Visualization results for 2 CNT with the chiral indices (5, 5) (*left*) and the chiral indices (15, 15), temperature $T = 273$ K



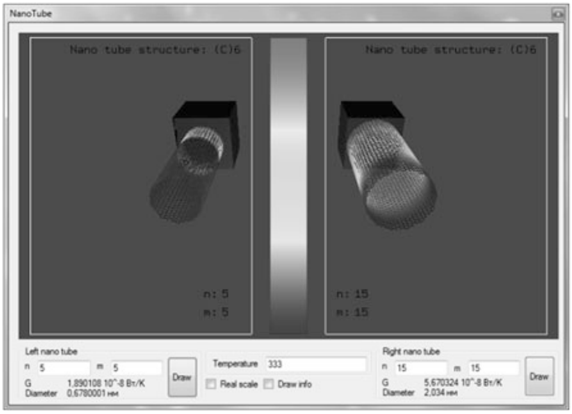


Fig. 5 Visualization results for 2 CNT with the chiral indices (5, 5) (*left*) and the chiral indices (15, 15), temperature $T = 333$ K

4 Conclusion

In the paper, we have described our approach to visual analytics support of CNT design automation. We have illustrated our approach using the single walled CNTs thermal conductivity as our test case. Our tool shows descriptors of CNTs. We use color-coding to represent thermal properties.

It is obvious that a designer can easily compare geometrical sizes of two CNTs and their thermal properties. The proposed descriptors approach supports evaluation and comparison of CNTs and simplifies design flow.

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A Model of Neurodynamics of Hippocampal Formation Neurons Performing Spatial Processing Based on Even Cyclic Inhibitory Networks

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Abstract This paper represents a model of neurodynamics of hippocampal formation cells involved in neural spatial representation. The model is based on the original neural scale-free even cyclic inhibitory networks and combines oscillation interference and attractor dynamics. Theta and gamma frequency oscillation interaction is concerned as the basic mechanism of spatially localized firing pattern formation. Grid maps of distinct scales and orientations corresponding to distinct entorhinal grid modules have been obtained.

Keywords Hippocampal formation · Place cells · Grid cells · Even cyclic inhibitory networks

1 Introduction

The formation of mental spatial representation by animals is associated with "cognitive map" construction. The hippocampus was proposed to be a site of cognitive map origin due to the discovery of "place cells" with highly localized in space activity [1]. Firing patterns of these cells, which are called "place fields", are small overlapping areas, tiling the environment. Every location is associated with the firing of particular group of neurons, or ensemble.

Later it was found that spatial representation arises on previous stages. It is connected with the discovery of "grid cells" in rat entorhinal cortex. Grid cells fire whenever the animal enters the set of environmental locations, situated in the nodes of hexagonal latitude [2].

Numerous mathematical models were proposed to investigate the mechanisms of the formation of firing patterns of these and other sells ("vector boundary cells", "head direction cells", "path cells", "time cells", etc.) and its interaction. These

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models are divided into two classes: oscillatory-interferential and attractor network models. The first class is based on under-threshold membrane potential oscillation interference. The second one relies on neural networks with specific architecture. Both classes have its advantages and disadvantages. This fact led to active development of models combining attractor-network and interference dynamics, see [3].

Despite numerous mathematical models, there is still no single agreement concerning spatially localized firing pattern generation. Furthermore, the mechanisms of different cell type interaction are unknown. Moreover, hippocampal and entorhinal microscheme organization is to be revealed. In order to answer these questions, it is necessary to consider neurophysiological phenomena together with the system role of these structure neurons.

2 Materials and Methods

The compound pending model of navigational behavior is based on the original scale-free neural even cyclic inhibitory networks, or ECI-networks [4]. The structural unit of ECI-network is oscillatory module. Each module is connected with others by weak recurrent inhibitory connections (Fig. 1, left). The detailed model descriptions are provided in [5].

Under the given parameters ECI-network generates two-frequency rhythm: low frequency rhythm is intermitted by bursts of high frequency oscillations. Relating to the modeling issue, these frequencies are assigned to theta and gamma ranges respectively.

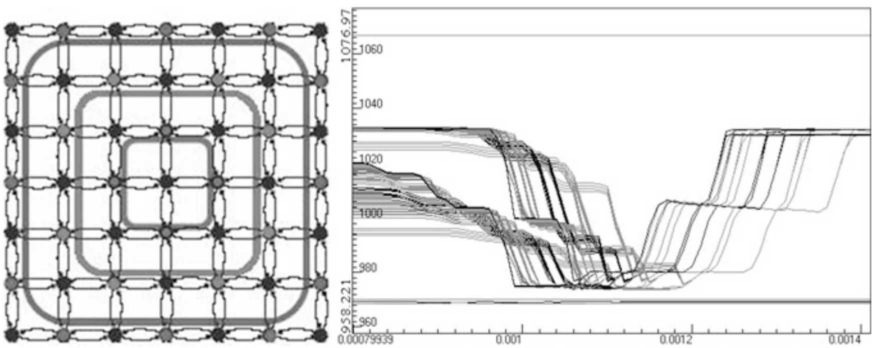

Fig. 1 *Left* Three-layered ECI-network scheme. Network layers are marked by *gray lines*. Informational units are depicted by *gray circles*, referent units are depicted by *black circles*. All oscillatory units are coupled by weak recurrent inhibitory connections. *Right* Oscillatory module phase response curves of 6-layered ECI-network. Different *shades of gray* correspond to informational units of different layers. *Horizontal lines* correspond to referent units. X-direction: contextual input amplitude. Y-direction: gamma-burst generation time. Contextual input is applied at [848–853]; informational inputs are applied to CCW (counter clock wise) clusters at [931–934], to CW (clock wise) clusters at [933–936]. Experiment 6k169exp-2f5-8.nex

ECI-network contains subsystem of referent units synchronized with zero relative phase shift. This subsystem sets time reckoning similar to “time cells”, found in the rat hippocampus [6]. Pulse signals of different amplitude and duration are applied to the inputs of informational unit subsystem. Depending on application time, input energy can shift high frequency bursts (or “gamma-bursts”) of informational units related to referent units. Total sum of all informational unit phase shifts composes phase code, depicted by phase response curves (Fig. 1, right).

Phase response curves are plotted according to the following algorithm. Two input types are applied in the computational experiments. The first one to be applied is contextual input, which is common for all informational units. This input determines intrinsic dynamical state of the network. Informational inputs, specific to each informational unit, are applied in subsequent oscillatory activity cycles (“theta cycles”). Due to ECI-network dynamical memory all inputs applied to informational units in different theta cycles are stored. They are represented in compressed state in the last (“referent”) cycle, which corresponds to the watch window. Informational unit phases relative to referent units are fixed in this referent theta cycle. Obtained phases for each informational unit are laid off along the Y–axis. X–axis represents contextual input value. Then network activity is reset and the calculations are done all over again with increased contextual input value. The value increment is constant during the whole experiment. Obtained sections assembled into continuous curves (Fig. 1, right).

3 Results

This section provides an example of grid map construction for two informational units of ECI-network and integrated space representation, performed by place cells. Let’s consider an experiment (6k169exp2f5-8.nex) with pulse contextual input applied in the ninth theta cycle and informational input applied in the tenth theta cycle. Phase response curves, obtained for this experiment, are depicted on Fig. 1, right. It is important to bring the notice that ECI-network is scale-free, that is why all parameters in the legends to the Figs. 1 and 2 are dimensionless.

Each oscillatory module of superior layer is coupled with 2 (referent units in the corner of network) or 3 modules, whereas oscillatory modules of other layers have 4 connections. It leads to the formation of topological informational unit ensembles with synchronized activity (the mechanisms of synchronized activity in ECI-network are considered in [7]). ECI-network attractor dynamics leads to the formation of local phase coherent steps in the right part of phase response curves (Fig. 1, right). These areas reflect synchronization of informational units of different ensembles and layers. These steps were previously shown to be neurodynamical correlates of triangular grid cell firing pattern [8]. On elaboration of this research an algorithm for local phase coherent step transformation into grid firing maps was developed.

Let the contextual input be associated with linear velocity and the informational input with angular velocity. Then contextual input amplitude determines radius and gamma burst phase determines angle in polar coordinates. Three local phase coherent steps correspond to the three dots of firing pattern, which can be completed to the hexagon (Fig. 2, left). It should be noted that the grids, plotted for the informational units of superior and inner layers, are shifted relative to each other, differ in scale and orientation. The angle between strait lines through points obtained from the first and the second local phase coherent steps for superior and inner layers constitutes 4.38°. This fact is in agreement with data about discrete organization of entorhinal cortex. According to this data grid cells form modules with different scales and orientations [9].

The distinction between grids, plotted for different layers, depends on the duration of network activity. Watch window shift to the right along the time axes results in enhanced distinctions.

The next point is to obtain place cell representation for this experiment. The model under development, as some others [10–12], considers grid cell output summation as the base of place field generation. The important feature of ECI-network is directional sensitivity [8]. Navigational behavior is assumed to be determined by population dynamics rather than by individual cells. Movement direction is determined by the weighted sum of gamma burst phases of neural ensembles with different preferred activity direction, clockwise (CW) or counter-clockwise (CCW). Such weighted summation results in integrated spatial representation provided by place cells (Fig. 2, right). The algorithm of grid cell output transformation into place cell firing can be found in [5, 13].

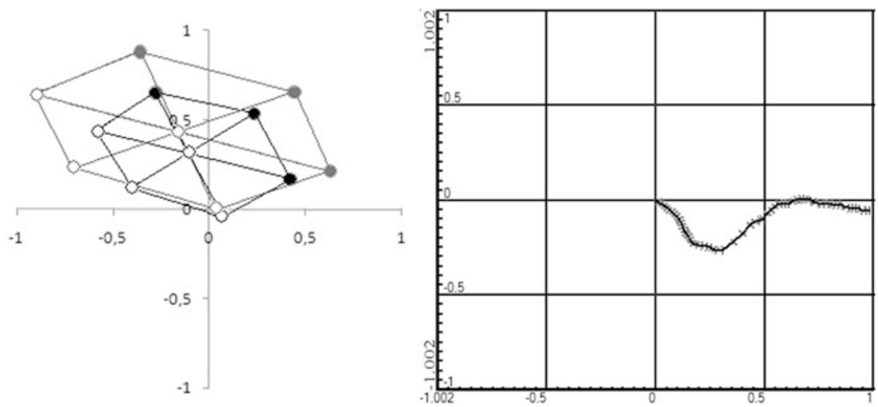

Fig. 2 *Left* Grid spatial representation of normalized space provided by informational units from the first, superior (*gray*) and the sixth, inner (*black*) layers of ECI-network. *Solid circles* indicate firing fields corresponding to the three local phase coherent steps. *Empty circles* indicate completed firing fields. *Right* Integrated place cell representation of normalized space. Each trajectory segment (separated by *gray dashes*) corresponds to one place field. Experiment 6k169exp-2f5-8.nex

4 Discussion

The model under consideration is a combined model of the navigational behavior neurodynamics. The original structure of the ECI-networks is in agreement with the neurophysiological data concerning wide spread occurrence of recurrent inhibitory networks in the hippocampal CA3 area [14] and in the entorhinal cortex [15].

Unlike models relying on frequency coding, this network takes phase coding approach. Spatial representation is considered to be based on theta-gamma frequency interaction. Such interaction is believed to be a fundamental principle of spatial processing in hippocampal formation [16–18]. Nevertheless, this mechanism is applied to the grid cell modeling for the first time.

The model allows obtaining grid cell firing maps of different scales and orientations. So different layers can correspond to different grid cell modules found in entorhinal cortex [9].

According to the model, grid cell outputs converge to form place fields. Nevertheless, path integration performed by grid cells is subject to error accumulation. This problem can be solved by the grid cell activity correction by feedback from place cells or by the information about environmental borders. Furthermore, it was found that stable place cell activity in juvenile rats develops simultaneously with border cells before the stable development of grid cell activity [19, 20]. Place cell activity is proposed to form from border cell outputs at the first postnatal days. Later it is corrected by grid cells. This correction should be more significant in the center of the environment. Due to this, further development of the model will be focused on border cell activity modeling and on the algorithm of grid and border cell output interaction for the formation of place cell firing fields.

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Feature Selection for Time-Series Prediction in Case of Undetermined Estimation

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Abstract The issues of factors selection are discussed in the article for the case when estimation of a set of factors is not stochastic. Here the quality comparison of two sets of factors is only possible with some probability, and modification of existing methods is required for their correct operation. For this purpose there is a suggestion of CGA Compact Genetic Algorithms to use the scheme of factor selection. For stochastic estimation of a set of factors the preparation stage is updated for genetic algorithms. The results are obtained for the standard benchmarks.

Keywords Data mining · Evolutionary computations · Neural networks · Feature selection

1 The State of the Feature Selection Problem

The Feature selection problem refers to the Data Preprocessing task in data Mining and Knowledge Discovery. In [21] the feature selection and the feature extraction tasks are being distinguished from the Data Preprocessing. Blum and Langley [5] divide the feature selection methods into embedded approach, filtering approach and wrapper approach.

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Traditionally, mathematical apparatus of correlation analysis, the detachment of linear dependences and others were used for the feature selection task. Baestans in [2] shows that for the dropping of insignificant input factor both the presence of high level correlation between this one and other input factors, and the lower level one between this input and output variable are possible. Hattingh and Kruger [13] use mixed integer linear programming for the combined removal of unimportant factors and for the filtration of data that cause the most noise in the prediction. The significance of factors is defined with the help of the linear model. Ahmad and Dey [1] use probability based method to extract significant attributes. Moerchen [18] offers the DWT and DFT based modified algorithm for the reduction of the set of data.

During the input factors interaction analysis Ezhov [7] uses Principal Component Analysis for the reduction of input dimension. It is based on the dropping of those inputs that have minor value of the covariance matrix, which takes into account only linear interaction. There one can observe the application of neural networks (NN), used for the realization of the nonlinear principal component method and allowing the high-order interactions. For the input factors and output variable interactions assessment it is suggested to use Box-counting algorithms based on calculation of the number of examples of Training Data boxes, into which the space of variables is divided. The suboptimal algorithm of the serial addition of significant inputs, which adds one more factor (that is the most significant together with selected ones) on every stage of its work to the select set, is also suggested there.

The use of genetic algorithms (GA) for the feature selection is justified and can compete with other methods in its efficiency. These methods are wrapper-methods. Freitas [8], Vafaie and De Jong [23] suggest the classical approach to coding to individuals and GA operators. The use of the classical approach is also shown by Guerra-Salcedo and Whitley [12], Vafaie and De Jong [23]. Minaei-Bidgoli and Punch [17] suggest using GA not only in factors selection, but also in determining their significance. In Hsu et al. [14] the GA are used not only in attribute selection, but in attribute partitioning too, that create new attributes based on the group of old ones. In Oh et al. works [19] as well as in Ezhov works [7] the idea of sequential adding/removal of the most/the least significant inputs is developed, having made the adding and removal of inputs a part of the hybrid genetic algorithm.

The idea of using GA as a set of factors selector combined with other methods such as classifiers is also known enough. Bala et al. [4] use GA as a “filter + wrapper” for a decision-tree learning algorithm, which directly carries out the classification. In Ibid, Raimer et al. works [21] GA is applied together with k-nearest neighbor algorithm. In Bala et al. works [3] GA is used for the factor selection and the decision tree serves as a predictor.

The combination “GA + NN” can be observed, for instance, in Gruau and Whitley works [11]. GA there is used for the creation of a grammar tree that yields both architecture and weights, specifying a particular neural network for solving specific Boolean functions. The neural networks are used in Yang and Honawar works [25] for classification. The selection of significant factors for the neural network is carried out by genetic algorithm, which estimates a multi-criteria task (the precision of the prediction and the cost of factor obtaining value).

But there are some conditions when an applicability of these methods has its limitations, and the delivered results are not optimal. In case when quality assessment of the specific data set has a stochastic nature, the application of the most methods is limited. For the qualitative assessment of every attribute subset, its multiple estimation is essential, and that requires an algorithm revision. Both neural networks and genetic algorithms which carry out the prediction can act as an environment for the stochastic quality assessment of the factors set. While selecting the specific influencing factors it is reasonable to use genetic algorithms.

The rest of this paper is organized as follows: Sect. 2 describes the formalizing of a factor selection problem. Section 3 describes the scheme of factors selection. Section 4 presents the compact genetic algorithm application for factors selection. Finally, Sect. 5 reports the practical results of presented system.

2 The Formalizing of a Factor Selection Problem

The problem of factors selection includes choosing a subset of d size from set of attributes of a total D number on the basis on the given optimization criterion. We shall indicate general source set of the data (the maximum possible number of tags) as U = {1, 2, …, D}.

On the other hand, a subset of the selected factors shall be indicated through X = {1, 2, …, d} while the set of remained (moved off) tags shall be indicated through Y. Thus, U = X ∪ Y.

After information transformation is carried out with its subsequent reduction, we do not operate U, but some *f*(U) range that is a functional transformation from U. Accordingly, X and Y are sets of selected and remote attributes of this transformed set. Thus, X ∪ Y = *f*(U).

For example, for the case of time series the data can be represented both in time and in frequency domain. By operating with time area we reduce a set of factors, while with frequency area we can also remove harmonics with low energy. Area of one to another transition is provided with Fourier transformation that plays a role of f(U). Besides, there is, for example, a factor analysis which also receives some set of the factors describing the given situation using functional data conversion of time series.

A criterion of quality estimation X shall be indicated as J(X) allowing evaluation of both the accuracy of a certain qualifier on a certain set of the data ("wrapper" approach) and a universal statistic unit ("filtering" approach). Anyway, the choice of J depends on a specific object.

The task of factor selection procedure is to find the set of X to satisfy the following condition:

$$\begin{cases} J(X) \to \max with \\ |X| \to \min \end{cases}, \tag{1}$$

where $|X|$ is the quantity of the attributes contained in X.

Thus, we have a multi-criteria problem that extremum may not be determined beforehand, being dependent of J(X) and a minimum threshold for $|X|$ set by the user.

3 Scheme of Factors Selection

There is a set of problems for which the result is not an exact estimation having been obtained with some probability. One of such problems is a classification using artificial intelligence methods. For example, classification with neural networks is not determined but contains some uncertainty. Moreover, evolutionary algorithms often find only suboptimal solutions thus it is possible to talk about the stochasticity of an issued solution. For example launching various programs (including training ones) can provide different results. In case of a problem of factors selection at forecasting its measure of quality is its value. Containing uncertainty is available in quality estimation of a data set.

As mentioned above, in case when stochasticity is received with an estimation of some subset of attributes to find an optimum set it is recommended to use the algorithms repeatedly estimating each of such set, in particular, genetic algorithms [9]. The scheme of factor selection is represented in Fig. 1.

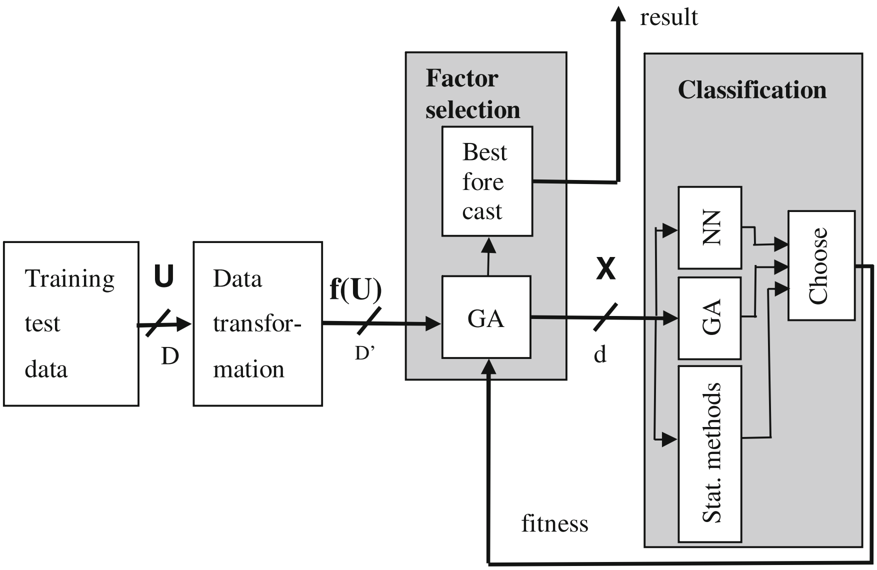

Fig. 1 Scheme of factors selection

In general terms the set of data U including training and testing data of the total number of factors D is a subject to transformation (feature extraction task). The transformed set of data f(U) with D′ number of factors shall be reduced using genetic algorithms. A reduced set of data X with $d = |X|$ is used for the forecast obtainments. So one can use any methods, both statistical and those of an artificial intelligence like neural networks or genetic algorithms. The choice of a method to be used can be done either optimality on the ground of the obtained forecast or by a user manually. One should notice however that when obtaining a forecast by means of statistical methods its result will not be a stochastic value, thus the idea of the given scheme gets lost. The obtained forecast value is used as fitness—function for genetic algorithm of factors selection. The forecast best value as well as the set of factors corresponding to this classification will be reserved being the result of factors selection system.

4 Compact Genetic Algorithm Application for Factors Selection

In Fig. 1 a genetic algorithm application for the factor selection is offered. In this case a definite kind of genetic algorithm should be selected considering simplicity and briefness of the algorithm as a fitness-function value shall be calculated for each chromosome in each epoch in any case.

In Haric et al. works [10], a CGA (Compact Genetic Algorithm) is proposed with its application efficiency investigation for optimization purposes. One should note that given approach permits an extremely simple soft- and hardware embodiment of the results being comparable with the classical genetic algorithm. Compact genetic algorithm scheme is represented in Fig. 2.

In CGA the population of binary individuals is substituted by probabilities vector for each bit of chromosomes and the probability of their zero (single) value is being presented. It allows the compact representation of binary chromosomes initial population. See Table 1 for example. The population (first four lines) can be represented in CGA by the following vector of probabilities (Pcga, the last line).

The essence of compact genetic algorithm is that each epoch makes its own new micro-population. It is generated based on the pointed vector of probabilities. Then the tournament selection is carried out where fitness-functions of all individuals of a micro-population are compared. The vector of probabilities is corrected after each comparison. The correction is done as follows: if alleles of a victor and a vanquished are of different values (0 and 1) the probability of the further generation being of a number positioned in the allele of the victor increases. In Haric et al. works [10] the step of change equals to 1/n, where n is the full size of algorithm population. After the tournament selection individuals are liquidated and formed again in the next epoch.

```
1.  Initialization of a probability vector
    for i:=1 to l do p[i]:=0.5;

2.  Generation of m individuals based on a probability vector
    for i:=1 to m do
    M[i]:=generate(p);

3.  Circular tournament execution
    for j:=1 to m-1 do
       for k:=j+1 to m do
       begin
         victor, vanquished:=evaluate(M[j],M[k])
4.             Updating a probability vector
               for l:=1 to length(M) do
                  if winner[l]<>loser[l] then
                  if winner[l]=1
                  then Pcga[l]:=Pcga[l]+chag
                  else Pcga[l]:=Pcga[l]-chag
               end
       end
    end

5.  Check a vector for convergence
    for i:=1 to l do
      if p[i]>0 and p[i]<1 then
       return to step 2;

6.  p represents final solution

Compact GA parameters:
n: population size
l: length of a chromosome
```

Fig. 2 The scheme of compact genetic algorithm

Table 1 Vector of probabilities in CGA

X1	X2	X3	X4	X5
1	0	1	1	0
1	0	0	1	0
1	0	1	1	0
0	0	0	1	1
0.75	**0**	**0.5**	**1**	**0.25**

Transition of all probability vector probabilities to stationary statuses (0 or 1) is a precondition of the algorithm work termination and is to be understood as complete determinacy of individuals' generation.

When we utilize genetic algorithms for factors selection, an individual is represented by a classical characteristic vector (where 1 in i position corresponds to i factor entrance in training data while 0 is its absence, the length of an individual is equal to the total number of all significant factors).

The fitness-function of forecasting problem is the forecasting error in the neural network for sampling, composed of factors encoded by an individual. The process of fitness-function obtainment is the following: training and testing data is made including the factors encoded by the given individual. Further training data is used for neural network training. We present input parameters of test data after training with NN and get an error of forecasting as a result of comparison of the NN parameters obtained on an output and calibrated values of test data. This error is used as a fitness-function. A peculiarity of the given CGA application is that the error of forecasting issued by the neural network is unstable and differs for same training data and test data at various sessions of training of the same NN. Thus, the fitness-function of an individual in CGA is a random quantity. Accordingly comparing two fitness-functions values, one can speak about one over another prevailing just with a certain probability. Calculating the individual fitness-function and consequently errors in forecasting this defect can be minimized in every epoch.

In algorithm an n parameter is present as the scale of the initial population remained as "an inheritance" of standard genetic algorithms and not based on structure of CGA itself. The size of change step of probabilities vector is based upon this parameter. Generally the given parameter can be taken absolutely arbitrary.

Let us assume that the value of the fitness-function is calculated correctly. We shall determine the step size for achieving an optimum in 1 epoch. Then with initial probability of each element of probabilities vector of p[i] = 0.5 and the size of micro-population m we have a set of equally probable states (0 or 1). The probability of choice of k1 ciphers and (k − k1) unities from the set containing m1 ciphers and (m − m1) unities is equal [6].

$$P = \frac{C_{m1}^{k1} * C_{m-m1}^{k-k1}}{C_m^k} \tag{2}$$

When comparing two values the probability of comparison between different notions of 0 and 1 for the set size = n (only in this case the modification of probability factor is available) is equally provided there is an updating of a probability vector for CGA:

$$P_h = \frac{C_{n/2}^1 * C_{n/2}^1}{C_n^2}. \tag{3}$$

The total amount of C_n^2 comparisons is executed to achieve an optimum for one CGA epoch and the size of step should comprise:

$$h = \frac{1}{C_n^2 * P_h} = \frac{1}{(C_{n/2}^1)^2}. \tag{4}$$

This statement is true for even number of chromosomes in population what is quite easily performed.

In case of incorrectness the fitness-function is described as a random number with mean value μ and deviation σ. Then in tournament a comparison is executed of the mean values and random quantities μ1 and μ2. When μ2 > μ1, the probability of an error equals to (Chernova [6]):

$$P_{err} = P(\mu_1 - \mu_2 < 0) = 1 - \Phi\left(\frac{\mu_1 - \mu_2}{\sqrt{\sigma_1^2 + \sigma_2^2}}\right), \tag{5}$$

where $\Phi(z) = \frac{1}{2\pi}\int_0^z e^{-\frac{z^2}{2}}dz$ is Laplace cumulative distribution function.

Thus, the size of step shall be corrected by the probability of wrong comparison of error. The size of the step is to be multiplied by P = 1 − 2 * Perr coefficient.

The next step change formula of vector of probabilities in CGA is:

$$h_m = h * (1 - 2 * P(\mu_1 - \mu_2 < 0)). \tag{6}$$

In the process of algorithm work the number of one and zero is changed being determined by Pcga probability vector. An average number of unities in chromosome is equal to:

$$SumPcga = \sum_{i=1}^{length(P_{CGA})=l} P_{CGA}[i]. \tag{7}$$

The probability of various values' comparison is reduced to:

$$P_h = \frac{C_{SumPcga}^1 * C_{l-SumPcga}^1}{C_l^2}. \tag{8}$$

Accordingly, the step of probability vector alteration must be increased:

$$\begin{aligned} h &= \frac{1}{C_n^2 * P_h} = \frac{C_l^2}{C_n^2 * C_{SumPcga}^1 * C_{l-SumPcga}^1} \\ &= \frac{C_l^2}{C_n^2 * SumPcga * (l - SumPcga)}. \end{aligned} \tag{9}$$

The final modified step looks like this:

$$h_m = \frac{C_l^2}{C_n^2 * SumPcga * (l - SumPcga)} * (1 - 2 * P(\mu_1 - \mu_2 < 0)). \tag{10}$$

Thus, the algorithm is developed for optimum attributes of subset for the case of stochastic quality estimation of this subset. As well as the quality estimation unit, the value of neural network output is used in classification. CGA (Compact Genetic Algorithms) are used as an adjustment algorithm of attributes subset. The change step for CGA vector of probabilities is modified considering estimation stochasticity.

5 Approbation and Practical Results

Approbation of CGA modified step results was concluded with benchmarks from Proben1 [20], UCI Library [22].

In each testing task the data distribution was reduced to an even form, thus improving the resulting accuracy. Classification results were obtained by NN on usual non transformed data (Untransform), on data transformed to uniform distribution (Uniform), on data with the reduced classic CGA factors set (CGA) as well as reduced CGA with modified CGA step (ModCGA). For the set of Glass 1 (Proben1, [20]) NN was trained on training data, test and validity data, and for the rest sets (Hepatitis and Ionosphere, UCI, [22]) a 3-fold cross-validation was performed: three sets of training data were created occupying the one–third of the sampling and being taken from the beginning, the middle and the end of data file. MSE results were obtained on training data (Training Error) and test data (Test Error) together with classification errors on train data (Training Class Error). For training data it was not an error of classification that was determined but classification accuracy (Test Class) due to the fact that in all sources this data was offered for those sets. A separate CGA was introduced for each of the sets, its results being tested on all versions of the set (three for 3-fold cross validation). To prove the quality of factors' set, NN was trained 60 times for each set, for each class separately (for example, for Glass 1 a total of 60 * 6 = 360 trainings of NN). The result was a mean value and a standard deviation of classification accuracy (Test Class) of all experiments for one set. Besides, for CGA the number of epochs was introduces for algorithm execution (Ep) and factors number in the set (Fact). The fitness function of CGA was classification accuracy on training data. Those components responsible for the set briefness were not utilized. The results obtained were compared to those by NN on (PCA + NN) sampling converted by means of principal component analysis as well as with those represented in Kwedlo and Kretowsky [16], Oh [19], Yang and Honavar [25] works. In Oh [19], Yang and Honavar [25] works the combination of GA+NN was also used, while in Kwedlo, Kretowsky works [16] it was C4.5 and EDRL.

Table 2 Results on Glass1 benchmark

Glass1 9 + 6, 214rec	Training error	Test error	Training class error	Test class	Ep	Fact
Untransform	2.83 (2.5)	12.26 (10.3)	2.88 (3.2)	**88.1 (11.2)**		
Uniform	4.59 (4.5)	11.01 (9.4)	5.50 (6.2)	**88.6 (10.7)**		
CGA	5.7 (4.1)	10.74 (10.5)	8.16 (6.1)	**90.32 (8.3)**	79	3
CGA Valid	5.71 (4.2)	10.59 (11.0)	8.15 (6.2)	**90.21 (8.1)**	79	3
ModCGA	4.22 (3.8)	10.04 (7.9)	5.39 (5.1)	**90.30 (7.4)**	78	4
ModCGA Valid	4.20 (3.8)	10.39 (9.4)	5.36 (5.0)	**90.13 (7.9)**	78	4
PCA + NN	0.77 (0.7)	17.47 (10.1)	0.34 (0.6)	**84.78 (10.8)**		6
Proben1 linear	8.83 (0.0)	9.98 (0.1)		**53.96 (2.2)**		
Proben1 mult 8 + 0 + 1			9.184	**67.92**		
Proben1 pivot	7.68 (0.8)		9.75 (0.4)	**61.97 (8.1)**		
In [25]				**70.5 (8.5)**		
In [25], GA				**80.8 (5.0)**		
In [19]				**100**		
In [16], C4.5				**67.5 (0.8)**		
In [16], EDRL				**66.7 (1.0)**		

As we can see in Tables 2, 3 and 4, the results obtained by CGA+NN combination with data reduced to the uniform condition actually exceed all results of similar works. A modified step introduction practically does not reduce the accuracy while the time for search is often reduced by an order, up to 90.6 %.

Table 3 Results on ionosphere benchmark

Ionosphere 34 + 2, 351rec	Training error	Dev	test error	Dev	Training class error	Dev	Test class	Dev	Ep	Fact
Uniform	0.52 (0.3)	0.38	3.84	1.51	0.00	0.04	97.89	2.28		
CGA	0.30	1.09	1.40	3.17	0.35	1.52	99.39	2.49	168 (49.4)	8.66 (6.3)
ModCGA	0.46	0.89	2.54	3.66	0.00	0.20	98.82	3.22	70.93 (52.0)	8.73 (4.0
PCA + NN	0.37	0.12	8.08	2.72	0.03	0.11	94.43	1.6		34
in [25]							94.30	5.00		
in [25]							98.60	2.40		
in [19]							91.45			

Table 4 Results on hepatitis benchmark

Hepatitis 19 + 1, 155rec	Training error	Dev	Test error	Dev	Training class error	Dev	Test class	Dev	Ep	Fact
Uniform	1.21	2.32	20.00	8.57	0.31	1.37	79.96	7.50		
CGA	4.50	1.56	16.62	13.86	4.90	3.89	82.53	9.83	160.67 (61.12)	8.67 (1.32)
ModCGA	3.49	12.14	18.27	23.07	3.40	10.02	82.04	12.3	15.33 (6.08)	10.50 (1.64)
PCA + NN	0.03	0.07	40.94	12.56	0.02	0.12	64.09	6.15		19
in [25]							84.70	9.50		
in [25]							97.1	4.30		
in [16] C4.5							79.6	0.60		
in [16] EDRL							81.2	1.80		

6 Conclusion

1. The conditions when classic methods of factors selection are insufficient and require modifications are determined. The stochasticity of estimation of subset factors is one of them. The optimum group of methods is chosen that is maximally suitable for work in such conditions. They are characterized by the repeated procedure of factors estimation. Genetic algorithms are mostly suitable for this purpose.
2. The conditions are stated when the estimation of attributes subset is stochastic. Such estimation is possible for the output of neural network or genetic algorithm utilized for classification
3. The scheme of factors selection is suggested. Its specific feature is that some data extraction is possible beforehand, for example, based on a factor analysis or Fourier transformation followed by the direct factors selection using a genetic algorithm. Then the forecasting is being developed on the ground of the resultant reduced factors set. The forecasting is used as fitness-function for the genetic algorithm of factor selection.
4. This type of genetic algorithm is chosen as the most suitable for fulfillment of such class of tasks. These are compact genetic algorithms. They are characterized by an outstanding simplicity of program realization together with considerable efficiency of work with such type of tasks.
5. For the condition of stochastic estimation the step of probability vector change for CGA got modified. Modification is based on determination of size dependence of probability vector change of the authenticity degree of two values comparison and namely estimation units of attributes subsets.

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A New Approach for Semantic Cognitive Maps Creation and Evaluation Based on Affix Relations

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Abstract This paper is devoted to a new method of creating semantic maps by means of affix relations. We show the differences between our approach and already existing ones. We also explain the necessity of our research, as it is unique for Russian language and our approach could be used in further researches and for creating semantic cognitive maps for Russian language. In the end of the paper we present the results of our work and further plans of our research.

Keywords Semantic map · Cognitive map · Weak semantic map · Affix · Affix relation · Lattice generator

1 Introduction

In the present time word semantics is given special attention in the Web and in other fields related with automated evaluation of word semantics. For instance, improving search in the Web (semantic search), where the user's queries are uniquely interpreted by the searcher, or sentiment analysis (also opinion mining), whose purpose is to determine the attitude of a speaker or a writer with respect to some topic of the overall contextual polarity (e.g. positive or negative) of a document [1]. This concept could be included into many different web-applications, as a rule in social networks, blogs and other resources of personalization, which the semantic search

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and sentiment analysis are applied in. In any case, automated evaluation of word semantics means using various scales, or dimensions, that characterize the word meaning [2]. These tools are also known as semantic maps, cognitive maps, semantic spaces.

The most popular approaches well-known in this field are based on usage of vector space model. It means that concepts, words or documents (representations) can be associated with vectors in an abstract multidimensional vector space. There are also other approaches the sense of which consists in using manifolds of more complex topology and geometry. In summary, cognitive map can be defined as a topological or metric space, the topology and/or the geometry of which reflect semantic characteristics and relations among a set of representations (such as words or word senses) embedded in this space.

Besides, there are other approaches, for example, named "weak semantic cognitive mapping" [3] that is not based on the idea of "dissimilarity". The idea of the current approach consists of using such notion as "opposite relations" and doesn't take into account individual semantic characteristics of representations given a priori. Only relations, but not semantic features, are given as input. As a result, semantic dimensions of the map that are not predefined to emerge naturally, starting from a randomly generated initial distribution of words in an abstract space with no a priori given semantics and following [3]. The main relation that authors use in this approach is the relation "synonymy-antonymy" for representations. Mainly the approach "week semantic cognitive mapping" was applied to the fixed quantity of English words.

According to different researches, in present time the most of these approaches are used for words of English language. Therefore, we have the designs of cognitive maps for English language and French language with defined metric for space of words [4–6]. In this connection we discover the opportunity of creation the cognitive map of Russian language, where each word will have certain space coordinates and will be easily identified.

2 Semantic Space Approaches

Latent semantic analysis (LSA, also known as Latent semantic indexing, LSI) has arguably received the most attention of all the semantic space model implementations [2, 7]. The principles of factor analysis, in particular the identification of latent semantic relationships of the studied phenomena or objects, are the basis of latent semantic analysis. This method is used to retrieve the context-dependent meanings of lexical units by means of statistical processing of a large corpus of texts in the classification or clustering documents. LSA represents the documents and individual words in a so-called "semantic space", in which all subsequent comparisons are performed.

The algorithm of LSA starts by computing a word × document frequency matrix from a large corpus of text, and in result it constitutes very sparse matrix. The row entries (vectors of words) corresponds to the frequency of each word in a particular document, and are normalized using an entropy function [2]. In next step the reduction of dimensionality of the sparse matrix achieved by using singular value decomposition (SVD; a mathematical technique closely related to eigenvector decomposition and factor analysis). It is compression step which is used to capture important regularities in the patterns of word co-occurrences while ignoring smaller variations that may be caused by idiosyncrasies in the word usage in individual documents. In other words, SVD brings out latent semantic relationships between words, even if they have never co-occurred in the same document [2, 8]. The result of condensing the matrix in this way is that words which occur in similar documents. LSA has the essential disadvantages and the one of them is related to the significant reduction in computation speed by increasing the size of input data (for example, in SVD-transformation) [9]. Besides, the current method has been criticized for being prone to the influence of strong orthographic word frequency effects (despite its entropy based normalization) on vectors and vector distances [10], and as being a "bag of words" model, ignoring statistical information inherent in word transitions within documents [11].

ConceptNet is a semantic network and an open-source project of Luminoso Technologies, Inc. Whereas similar large-scale semantic knowledgebase like WordNet are carefully handcrafted, ConceptNet is generated automatically from the 700,000 sentences of the Open Mind Common Sense Project (OMCS)—a World Wide Web based collaboration with over 14,000 authors [12, 13]. ConceptNet is expressed as a directed graph whose nodes are concepts, and whose edges are assertions of common sense about these concepts. Concepts represent sets of closely related natural language phrases, which could be noun phrases, verb phrases, adjective phrases, or clauses [14]. Commonsense knowledge in ConceptNet encompasses the spatial, physical, social, temporal, and psychological aspects of everyday life.

Latent Dirichlet Allocation (LDA) is a generative topic model for explaining the observations by using the implicit groups to provide an explanation of why some of the data are similar. LDA was first presented by Bleem David, Andrew Ng and Michael Jordan in 2002 and it was a graphical model for detecting topics [15]. If the observations are the words collected in texts, it argues that each text is a mixture of a small amount of topics and that the appearance of each word is related to the one of the topics of the document. In summary, in LDA, each document may be considered as a mixture of various topics. A topic is not strongly defined, neither semantically nor epistemologically, and is identified on the basis of supervised labeling and (manual) pruning on the basis of their likelihood of co-occurrence. A lexical word may occur in several topics with a different probability, however, with a different typical set of neighboring words in each topic [16].

Weak semantic cognitive map is a kind of semantic spaces that provide metrics for universal semantic dimensions. The idea of weak semantic cognitive mapping [17] is essentially differs from LSA and LDA approaches, above-mentioned in this paragraph and based on the notion "dissimilarity", and consists of separating representations (e.g. words) along as many as possible clearly identified, mutually independent, universal semantic dimensions that make sense for all domains of knowledge. Word-to-word relations of antonymy, synonymy, hyponymy and hypernymy are used in construction of the maps. The emergent semantic map dimensions are: “valence” (the first principal component of the weak semantic map derived from synonym-antonym relations), “arousal” (the second principal component), and “abstractness”, or ontological generality (the semantic dimension derived from hypernym-hyponym relations) [18].

3 Features of the New Approach

Previously there were considered mostly English kinds of semantic maps. For Russian language for the moment there is no fully working algorithms for creating semantic maps. The closest decision was offered by so called Russian WordNet team, which decided to create a Russian analogy of the English WordNet version. For this moment their task is half done, but anyway their progress is very small. It is connected to some difficulties mostly caused by translation of synsets (sets of synonymic words).

The other researches in this area weren’t so successful, even in comparison to Russian WordNet. For this moment, the semantic map area is quite unexplored. In this connection we have started our research to try to solve this problem.

During our following researches we are going to introduce a fundamentally new approach of creating semantic maps for Russian language. There we highlighted the most common problems, which we can face during our research and the methods which could help us to avoid them.

1. Variety of Russian words. There is huge amount of Russian words which meaning is quite close and the only difference between them are affixes. In Russian language these words are called «same root». To solve this problem, it was decided to extract the root of each word and place it on the map. As the addition of some affixes to the root as a rule (except some affixes) can create definite appraisal of the word, therefore using the special functions and algorithms we will be able to find the positions of the new words without placing it on the semantic map. This approach will help to reduce the semantic map size and difficulty without losing its expressive power.
2. Complicated morphological structure of Russian word. Each word in Russian language, in the simplest case, consists of the root, sets of suffixes and prefixes, postfixes and inflexions. However, there are plenty of exceptions of this rule, or the words, including quite big amount of affixes. To handle of these words, we have to use huge dictionaries and be well versed in the area of morphology.
3. Variety of synonyms and antonyms. The expressiveness of Russian language is higher than for English languages, therefore there are plenty of synonyms and antonyms of each word. To simplify the semantic map and make the relation of synonymy and antonymy more formalized it was decided to add special

relationships of the words. These relationships will be defined through the special coefficients. For example, is two words are synonyms, the coefficient of synonymy between them will be 1, if they are antonyms it will be −1, in other case it will be 0. Adding this relation will make the map easier for analysis and usage.

4 The Representation of the Word Structure

For the emotional color shaping of words in the Russian language we normally use suffixes. Prefixes may also be used to increase or decrease the meaning of the words, but less than suffixes. Therefore, each affix may specify a certain emotional color. If the prefix or suffix does not affect the meaning of the word, but simply forms a new part of speech, we will consider that it sets a zero emotional color. In the table below we represent the classification of the most common Russian suffixes and show whether they can attach the appraisal to the word or not.

In Russian language, every word can be represented as concatenation of three sets (ordering elements in concatenation may depend on the particular case)

$$W = \langle R, a_1, \ldots, a_n, b_1, \ldots, b_m \rangle, \quad m, n \geq 0, \tag{1}$$

where

W described word,
R root of the word,
$\{a_i\}$ nullable set of affixes (suffixes, prefixes, postfixes)
$\{b_i\}$ nullable set of other elements (ending and so on).

Generally, removing an affix from any word converts it into another word, which is also available in the lexicon. Thus, each affix determines its relation type on the set of the words. If each word has some coordinates on semantic map then each affix can be associated with a vector of a typical shift, caused by adding affix to the word. These vectors can be considered as lattice generators.

This approach has several advantages. Firstly, it is a perceptible reduction of computational complexity, since there are about a hundred different affixes in Russian language. Thus, instead of positioning each word form to a semantic map we only need to arrange the root of words. Another obvious advantage of this method is a better allocation of emotional color and style of speech or text, based on the analysis using affixes that will help in further research of modeling the process of human thought and activity.

Moreover, the relatively small number of words associated with affixes that can evaluate semantic shift of the coordinates. If we throw out the card all the words that are not related by affixes, the map will be very small. And in the dictionary there are a plenty of words that are so unrelated, that effect of affix relationship on semantic map will be imperceptible. Despite these difficulties, the use of affixes can sometimes be useful as assistant for main semantic map construction method.

5 Conclusion

The rapid growth of interest in the area of automated proceeding and recognition texts extracted from different documents or the Internet or its usage by automated systems with considering its emotional color, shows us the necessity of designing the semantic cognitive map for Russian language. We considered the most popular semantic maps, designed for different languages and found out that there is now fully completed cognitive map for Russian language.

The basis of our approach is usage of affixes to define the emotional colors of the words. We represented the set-theoretical model of the Russian word considering all the Russian morphemes. By the means of this model we can describe each Russian word.

Using the special algorithms and the described model we can create a fully working semantic map for Russian language. It will have many advantages including, for example, its calculating power.

Our further plans of this research include the developing the calculating algorithm which will help us to create semantic map. We are also going to test in on different dictionaries and check its calculating power.

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On Alternative Instruments for the fMRI Data Analysis: General Linear Model Versus Algebraic Topology Approach

Irina Knyazeva, Vyacheslav Orlov, Vadim Ushakov, Nikolay Makarenko and Boris Velichkovsky

Abstract This work aimed at comparing two different approaches (classical general linear model based on the Bayesian approach and the method of algebraic topology) for fMRI data processing in a simple motor task. Subjects imposes block paradigm, consisting of three identical blocks. The duration of each block was 40 s (20 s of rest and 20 s of right hand fingers busting). To obtain statistically significant results were carried out 20 sessions of experiment. The results obtained by both methods were very close to each other, but correspondence between statistically significant changes in BOLD-signal was not quite complete. TDA (topologic data analyses) allocated additional voxels in Post central gyrus right. This region could be revealed with the changing in the level of confidence in the GLM model, but with this lower level of confidence too much additional voxels appeared. Combination of two approaches could be used for verification of results.

Keywords fMRI · Activation detection · General linear model · Time series analysis · Topological data analysis

1 Introduction

This work is devoted to the peculiarities of fMRI data analysis in the neural network activity localization. The relative changes in BOLD-signal associated with the neural network activity are rather weak, of the order of 2–6 % in the response.

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A large number of methods have been proposed to analyze fMRI data. They could be roughly divided on two groups: model based and data driven [7]. The most popular model based approach is statistical parametric mapping (SPM). SPM based on joint using general linear model (GLM) and Gaussian random field theory to make statistically significant inference about spatially extended data through statistical parametric maps [5]. Using GLM with fMRI data has several intrinsic assumptions that do not always hold in real experiments. For example, response between input stimulation and brain response is linear and the HRF function is the same for all voxels. But different brain areas may have different hemodynamic responses and many non-linear changes could influence the BOLD signal. These cases cannot be accurately reflected in linear model. Another problem of all model based approaches that they based not on the intrinsic structure of the data, but on the supposed response to the experimental events. Besides GLM methods there are other model-based methods [6]. There is also a variety of model free and non-parametric methods developed for detecting brain activations in fMRI [1, 3, 8]. They do not require any prior knowledge about the experiment or the hemodynamic reactions. In case of clustering there is a problem of results instability and local maxima. In paper [2], two approaches, PCA (Principal Component Analysis) and fuzzy clustering are compared on simulated dataset. The authors show that clustering outperforms PCA and conclude that data driven approaches could be used complementary to statistical inference methods.

Despite of this abundance of methods all of them have their-own advantages and disadvantages, so that the task of effective estimation of brain local activity remains highly acute. In the present study, we would like to propose a new data driven approach based on topological analysis for the individual time series. The theoretical framework for this method was developed by Perea and Harer [9], who borrowed main ideas from the new field of algebraic (or computational) topology. In the present work, we for the first time applied this topological approach together with statistical (Bayesian) parametric mapping realized in SPM8 software to the results for a finger tapping experiment.

2 Materials and Methods

4 subjects (1 man and 3 women aged from 21 to 23) participated in the experiment. Their task was to perform simple motor tapping task while BOLD-signal changes were registering during several sessions of the same block-designed experiment. We used the echo planar fMRI sequences of two types: with/without time delay of 500 ms between the serial readout fMRI signal (collecting slices method is interleaved, TR = 2000 ms, TE = 25 ms, voxel size $3 \times 3 \times 3$ mm^3). Subjects imposes block paradigm, shown in Fig. 1. Block time (rest + bust fingers of the right hand) was 40, 20 s for rest and 20 s for tapping. For each subject was conducted 10 series fMRI scans (5 episodes without delay and 5 series with a time delay of 500 ms).

Fig. 1 Experimental paradigm

2.1 Preprocessing

fMRI data preprocessing for both methods is identical. Structural and functional data were given to the center in the anterior commissure. After that images were normalized to template images (T1-template for structural and EPI template for functional) with 2 × 2 ×2 mm^3 voxel size in MNI (montreal neurological institute) coordinate system. On this step was computed the warp that best registers a source image to match a template. fMRI data were additionally corrected for magnetic field inhomogeneity. Functional data were co-registered to the structural data. For noise and effects due to residual differences in functional data suppression we smoothed it with a Gaussian kernel of 8 × 8 × 8 mm^3 width.

2.2 GLM

During the experiment we measure a response variable Y_j (BOLD signal in a particular voxel), where j is the observation index. Then we suppose that for each observation we have a set of L ($L < J$) explanatory variables. The explanatory variables may be discrete (often continuous) covariates indicating the levels of an experimental factor. General linear model finds the solution as a linear combination of the explanatory variables plus an error. We specify GLM design matrix (onsets and duration of each condition). After that model parameters are estimated using restricted maximum likelihood. It assumes the error correlation structure is the same at each voxel. As a final step we interrogate results using contrast vectors (corresponding to comparable conditions) to produce statistical parametric maps ($p < 0.05$ with family wise error correction FWE).

2.3 Algebraic Topology

The whole description and theoretical proofs of the approach could be find in [9]. Here we briefly cover the main idea, which is as follows. Lets consider the time series in which there is some kind of repetitive pattern. It is assumed that the length of this repeat structure or period is known and repeats at least twice. After that we need to perform time delay embedding, well known in the field of dynamical system studying [10]. For this, select the window size is approximately equal to the period and slide with this window along the time series. We will call this window as sliding window. As a result original time series breaks down to the overlapping fragments. Lets take one fragment. Suppose, that we can define continuous function f for this discrete fragment. It could be always done with the approximation of time series. After that, we need to take integer number M and the step τ. For sliding window with the starting point t, the point in $M+1$ space will be defined as: $SW_{M,\tau}f(t) = [f(t), f(t+\tau), \ldots, f(t+M\tau)]$.

Going through all the values of we obtain a cloud of points in space. After that for each point the procedure of normalization was performed.

This procedure ameliorates the effects of dampening and trending in the original time series, and also makes the method non-sensitive to amplitude modulation. It appears that in the case where the window length $w = M\tau$ is approximately equal to the length of the cycle, the cloud of points in this space forms a ring. At Fig. 2 there is example of random time series and sinus and corresponding points cloud for $M = 14$ projected to three coordinates.

For the analysis of structures in a point clouds, there well developed mathematical apparatus, which relates to the field of algebraic topology [4]. In terms of algebraic topology the appearance of the ring like structure in the points cloud corresponds to appearing of one-dimensional cycle. The stability of this cycle can be estimated using the so-called persistent homology. In this approach, each point is surrounded by a sphere of radius r, and then estimated how the number of connected components and cycles changes with an increase of r. The moments, in this case value r, at which components or cycles appeared or disappeared are recorded. It is convenient to represent the lifetime of the component in the form of lines or bars, referred to as barcodes. The value corresponds to the appearance of barcode called a birth b and death d, disappearance.

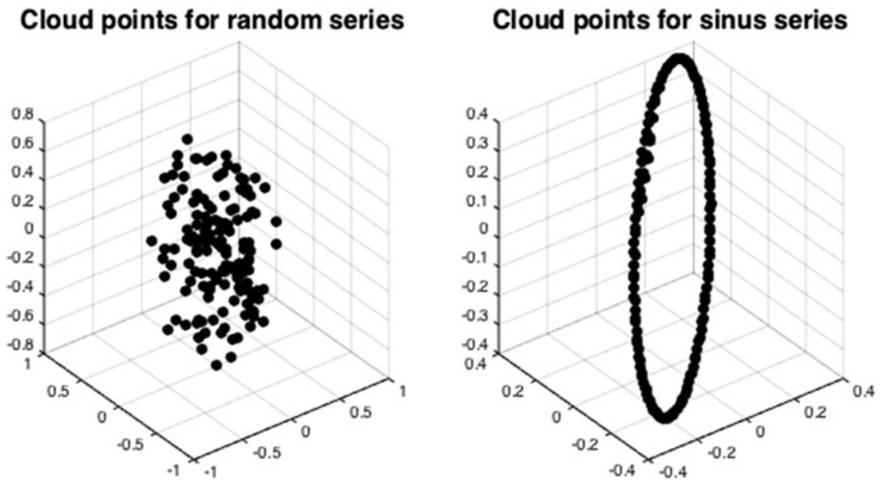

Fig. 2 Point clouds in dimension 15, projected to three coordinates, formed with the sliding window for random and sinus time series

The number of cycles in the points cloud could be different, but is was proved in [9] that in the presence of a periodic structure could be measured by the maximum length of barcode. That is, if there is a periodical structure in the time series, than there will be at least one one-dimensional cycle or one-dimensional hole. The higher the value—the higher level of periodicity in the signal is present. The score factor take zero value for periodic time series and 1 for non periodic for the different values n, m.

3 Results

The proposed methods were tested on the popular finger tapping task. For all voxels time courses the score factor and T criteria (Student's t-test) were estimated (at the Fig. 3).

The main activation region was detected with the both approach, but with the topological approach additional regions were detected. Also we examine several active voxel rejected with the SPM and accepted with topological score factor are shown in Fig. 4.

As a result of the analysis, the data for zero delay, and the data for 500 ms delay of 10 sets of statistically significant BOLD-signal changes stably maintained in 9 cases in the motor cortex of contralateral hemisphere and 8 cases ipsilateral cerebellum. Thus, even in the case of block designed paradigm activation effect patterns of movement detected by fMRI method can be unstable. Note that this is not due to the subjects fatigue.

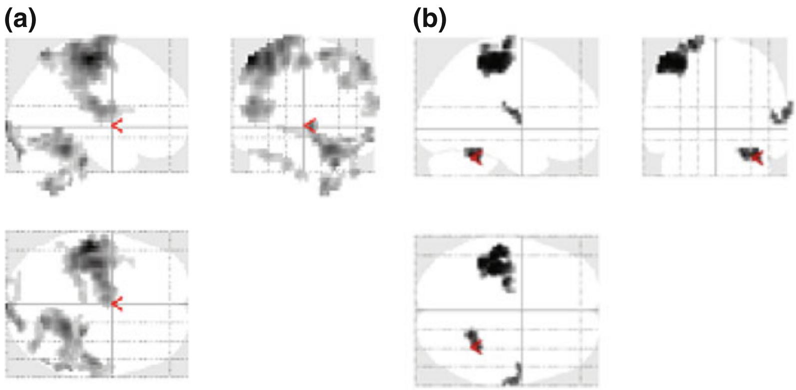

Fig. 3 Activation maps examples for finger tapping experiment. **a** $p < 0.05$ FWE. **b** algebraic topology approach

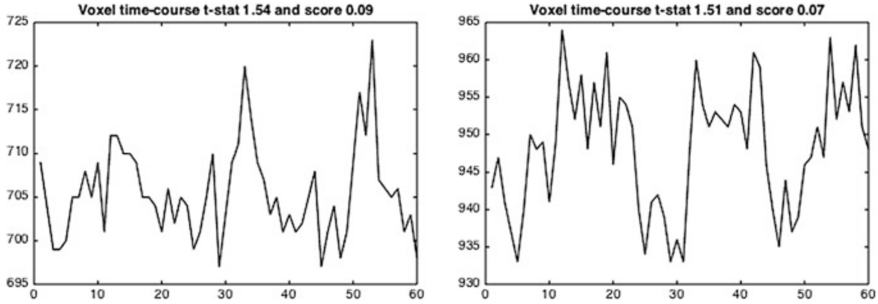

Fig. 4 Two examples of voxels time courses rejected with the SPM and detected with the score factor estimation

4 Discussion

Correspondence between statistically significant changes in BOLD-signal was not quite complete: TDA (topologic data analyses) allocated additional voxels in Post central gyrus right. However, changing in the level of confidence in the GLM model to the level of $p = 0.001$ without correction for multiple comparisons FWE or for $p = 0.01$ with minimum cluster size 100 voxels also revealed the presence of changes in BOLD-signal in this area.

Our results confirm the initial hypothesis of this study that the data driven topological approach for periodic component estimation could be applied in the task of activation detection on fMRI time series in case of block designed paradigm along as other models. Moreover, it could be used in the other task arises during fMRI data exploration connected with periodic component extraction, for example cardiac induced signal change. Potentially it could be even more sensitive screening method with respect to the standard GLM modeling. In a further perspective on the topological approach it could be combined with aperiodic and pseudorandom schemes of experiment which are of increasing importance for the neighbor discipline of brain-computer interface [11].

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Application of Hopfield Neural Network to the N-Queens Problem

Andrei A. Lapushkin

Abstract This paper describes one of the methods to use Hopfield neural network in combinatorial optimization. This subject has many problems and one of them is the N-Queens problem. The algorithm for solving this problem is written in Matlab and the results can be shown as an $N \times N$ chessboard with N-Queens.

Keywords Hopfield network · N-Queens problem · Optimization · Lyapunov function

1 Introduction

Neural networks are currently used in many areas of automation. There are a lot of different kinds of neural networks: from simple perceptron to complex specific networks. Here I will show Hopfield neural networks and one of its applications. Hopfield neural network [1] is a single-layer network where the output of each neuron is connected to the inputs of other neurons. Hopfield network is shown in the Fig. 1. The dynamics of these networks converges to one of the equilibria. These equilibrium positions are local minimums of the functional, called the energy of network. This network can be used as auto-associative memory or filter, so that it

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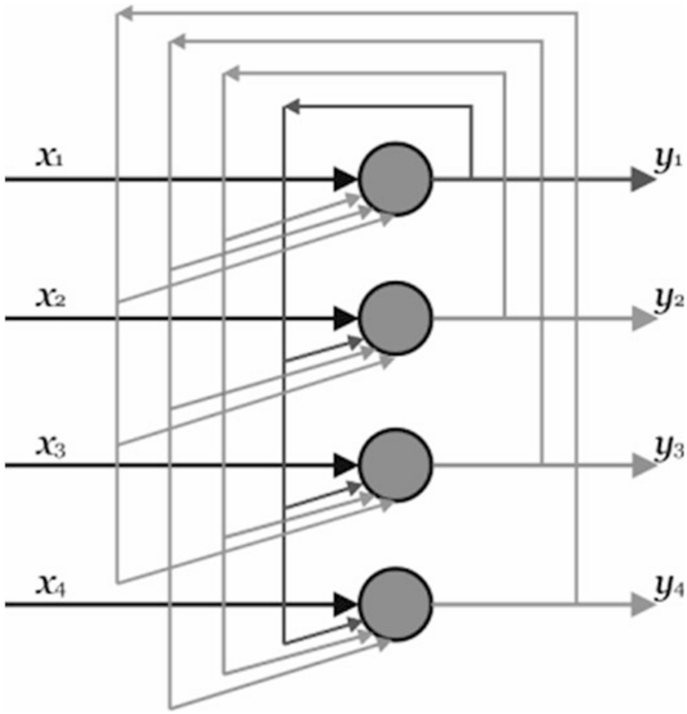

Fig. 1 Hopfield network

is able to restore the damaged image on the stored reference basis [2]. Hopfield network is used not only for restoring visual images but also for solving combinatorial optimization problems if the problem can be formulated as an energy minimization problem. Some examples of these tasks are: Travelling salesman problem, Assignment problem, Eight queens puzzle, etc. Let us consider the application of Hopfield network in the last one.

In mathematics, this problem can be formulated as: Fill the $N \times N$ matrix with zeros and ones so that the sum of each column, row and each diagonal does not exceed 1 and the total number of units is equal to N. The matrix is like a chessboard and the units are queens. This is a table [3] where total and unique solutions are presented. For example, for 8-queens problem there are 92 total and only 12 unique solutions, but for 25-queens problem there are more than 2 quadrillions (10^{15}) total and about 0.3 quadrillions unique solutions. Thus, it is highly undesirable to solve this problem with exhaustive search because solution time exponentially grows with a dimension increase. Therefore, there are different stochastic search algorithms for this task, such as a genetic algorithm [4, 5].

2 How to Use Hopfield Energy Function to Solve the N-Queens Problem

In order to apply Hopfield network for solving this problem, it is required to describe energy function that the neural network will minimize. This function is also called Lyapunov function [6] for systems with feedback and it can be represented as:

$$E = -\frac{1}{2}\sum_{i}\sum_{j} W_{ij}Y_iY_j - \sum_{j} W_{0j}Y_j + \sum_{j} T_jY_j\,, \tag{1}$$

where E is the energy function, W_{ij} is the weight of input neuron i to the output neuron j, Y_i is output neuron i, Y_j is output neuron j, W_{0j} is bias weight neuron j, T_j is the threshold of neuron j.

The solution of the problem will be a chessboard with queens on it which are disposed in accordance with the requirements reviewed above. Now we can describe the energy function of Hopfield network for N-queens problem. The function has to be minimal only when there is nothing in the row, the column and the adjacent diagonals:

$$E = A\sum_{x}^{N}\left(\sum_{j}^{N} V_{xj} - 1\right) + B\sum_{i}^{N}\left(\sum_{y}^{N} V_{yi} - 1\right) + C\left(\sum_{\substack{1\le x+j\le N\\ 1\le i+j\le N\\ j\ne 0}} V_{x+j,i+j} + \sum_{\substack{1\le x-j\le N\\ 1\le i-j\le N\\ j\ne 0}} V_{x-j,i-j} - 1\right), \tag{2}$$

where A, B, C are the coefficients of Lyapunov function, N is the dimension of the problem, V_{xj} is the value of V matrix in the row x and in the column j.

There are other methods to use Hopfield network for the N-Queens problem. In [7], the authors use their own “trial-and-error” technique. They also calculate weight function and its dynamics. This algorithm minimizes Lyapunov function and stops when some value of time is reached. Also, the optimal competitive Hopfield model can be applied to this problem [8]. The model guarantees the descent of any energy function once the groups of neurons are updated.

In this paper only minimization of the energy function is offered; the values of network weights are not required. The algorithm has been implemented in the mathematical package Matlab. Here is the code of M-file:

```
%Problem size
N = 20;
Amount = 0;
%count iterations
num = 0;
%main loop
while (amount ~= N)
    amount = 0;
    L1 = 0;L2 = 0;L3 = 0;L4 = 0;
    E = zeros(N);
    V = zeros(N);
%Sub Loop = Hopfield network
     for I = 1:N*N
%Random numbers from 1 to N
        i = randi(N);
        j = randi(N);
%Number of queens in raws
        L1 = sum(V(i,:));
%Number of queens in columns
        L2 = sum(V(:,j));
% Number of queens in diagonals
        L3 = sum(diag(V,j - i));
        L4 = sum(diag(fliplr(V),(N – j + 1)- i)); %N-j+1
- new j
%Count energy, coefficients A,B,C are equally 1
        E(i,j) = (L1 - 1) + (L2 - 1) + (L3 + L4 - 1);
%The reason for stopping the algorithm:
%there are N-Queens at the board(amount=N)
%none of them is under attack
        if  E(i,j) == -3
            V(i,j) = 1;
            amount = amount + 1;
        end
    end
num = num + 1;
end
%The image of the board with Queens
K = 256 * ones(N + 1);
colormap(gray(256));
for I = 1:N;
    for j = 1:N;
        if V(i,j) == 1;
            K(i,j) = 0;
        end;
    end;
end;
pcolor(K)
```

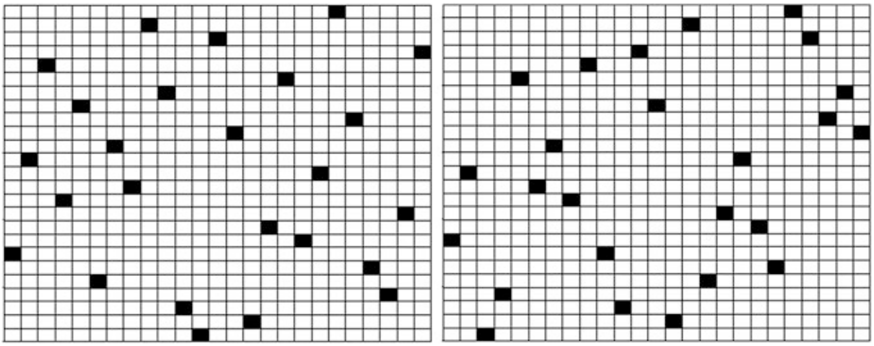

Fig. 2 Results for the 25-queens problem

The description of the algorithm is given below:

In the beginning, we select the N dimension of a chessboard. Next, the algorithm has two loops: the main loop and the sub loop. The first one checks that the number of queens is the same as dimension of our chessboard. In this loop, the variables that count the number of queens in rows, columns and diagonals are reset and two zero-matrixes, the matrix of neurons (V) and the matrix of energy (E), are formed. The second one solves the N-queen problem. As a possible queen's position is chosen randomly, it should require some extra attempts to get a queen to the right place (instead of checking it N times, the algorithm checks it $N * N$ times). In this loop, the number of queens in each row, column and diagonal is count. The variables i and j are coordinates in a row and in a column, respectively. Further the energy is calculated in a selected coordinate (the coefficients of Lyapunov function are assumed equal to one) and if the energy is minimal (the minimum value is -3), the unit is placed in this coordinate and the total number of queens on the board is increased by one. If the V matrix has a unit, it means it has a queen; if it has a zero—there is no queen. After solving the problem, the algorithm creates a chessboard with queens on the right places (shaded cell).

Figure 2 shows some results for the 25-queen problem.

Table 1 shows average iterations of algorithm with different N sizes of the problem.

In [7], the results are given to the problem dimension of more than 30 and average iterations for 200-queens problem are 358. On the other hand, the meaning of iteration in our works is different. For my algorithm, "an iteration" is when the algorithm does not find an appropriate solution and it starts again, and for the paper, "an iteration" is a change of weight function.

Table 1 Average number of the algorithm iterations

Problem size (N)	5	8	10	15	20	25
Average iterations	17	125	273	1354	8570	17,140

3 Conclusion

In this paper, I presented a way to use Hopfield network as a minimization algorithm. If the size is more than 25, it takes unsuitably much time to solve this problem. But for the sizes less than 25 the time is acceptable. The algorithm is based only on the values of energy function in this paper.

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Simulation of a Fear-like State on a Model of Dopamine System of Rat Brain

Alexey Leukhin, Max Talanov, Ilia Sozutov, Jordi Vallverdú and Alexander Toschev

Abstract In this paper we present the following hypothesis: the neuromodulatory mechanisms that control the emotional states of mammals could be translated and re-implemented in a computer by means of controlling the computational performance of a hosted computational system. In our specific implementation we represent the simulation of the fear-like state based on the three dimensional neuromodulatory model of affects (here the basic emotional inborn states) that we have inherited from works of Hugo Lövheim. We have managed to simulate 1000 ms of work of the dopamine system using NEST Neural Simulation Tool and the rat brain as the model. We also present the results of that simulation and evaluate them to validate the overall correctness of our hypothesis.

Keywords Dopamine · Fear · Artificial intelligence · Simulation · Rat brain · Affective computing · Emotion modeling · Neuromodulation

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1 Introduction

Current rapid development of neurocognitive sciences and new discoveries of mechanisms of natural intelligence trigger new insights and opportunities in the field of biologically inspired cognitive systems. It is more evident now that emotions play a significant role in natural intelligence and adaptive behavior [2, 8]. We still can indicate the lack of effective universal models of emotional mechanisms, which could be implemented as artificial cognitive architectures.

The intrinsic value of emotions for the running of cognitive processes is still undervalued by researchers, who make a behaviorist approach to artificial emotions based on basic observable actions. Our model introduces a neuromodulatory mechanism to simulate the emotional states and their influence over cognitive processes. This represents a milestone into the creation of new generation AI intelligences which will possess neuromodulatory architectures able to run over several conceptual models, languages and systems, creating unique and plastic cognitive identities, like humans beings do. This is a basic but solid first step towards grounded cognitive systems that share the same controlling mechanisms of synthetic neuromodulators across the whole cognitive multiheuristic architecture.

2 The Problem

During the last two decades several researchers have demonstrated that emotions and a broad set of phenomena related to them are tightly connected to cognition and thinking [2]. There could be several interesting perspectives of the problem of the re-implementation of emotions: philosophical, psychological and neurobiological [1]. In this paper we present one neuropsychological model of influences of emotional neurobiological processes on thinking and thus computational processes via neuromodulation.

We also have to mention the importance of emotional simulations for the research on mental disorders as well as the understanding of complex and still not completely understood actions like creativity, concentration or interest. Emotions are a fundamental part of the cognitive processes, being involved into very important processes like attention, motivation, strategy selection, mood disposal, reaction, invention, among a long list.

New research methods, especially from the neuroscience, have increased the amount of the data regarding a human brain performance: EEG, fMRI provided the proper background for the breakthrough in the neuroscience. This was the basement for some authors, such as Llinás [5], to create the descriptions of the emergence of consciousness, and AI researchers introduced several ideas regarding the emotional processing.

Hugo Lövheim [6] based his theory on a three-dimensional model of emotions and monoamine neurotransmitters (*serotonin, dopamine, noradrenaline*). Vertexes of the model are affects, as defined by the Tomkins, who describes eight basic emotions Tomkins referred to basic emotions as “innate affects”, where affect, in his theory, stands for the “strictly biological portion of emotion”. According to this theory, the eight basic emotions are: *enjoyment/joy, interest/excitement, surprise, anger/rage, disgust, distress/anguish, fear/terror and shame/humiliation*.

3 Our Idea

We have extended the original “cube of emotions” via mapping to the computational systems parameters (see Fig. 1): computing power utilization, computing power distribution, memory distribution, storage volume and bandwidth, memory and storage. More specifically, the parameters taken into account are:

Computing utilization is a metric able to quantify how busy the processing resources of the system are. It can be expressed by the average value of all the single processing resources’ utilization.
Computing distribution aims at quantifying the load balancing among processing resources. It can be expressed as the variance of single resources’ utilization.
Memory distribution is associated with the amount of memory allocated to the processing resources. It can be quantified by the variance of the amount of memory per single resource.
Storage volume is an index related to the amount of data and information used by the system.
Storage bandwidth quantifies the number of connections between resources, i.e. processing and data nodes.

For the further details please see our previous articles: [1, 10, 11].

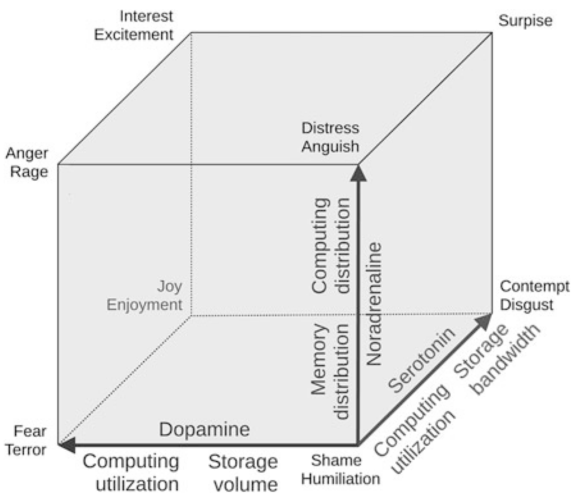

Fig. 1 The correlation of emotional states with monoamines levels and computational system parameters, based on [6]

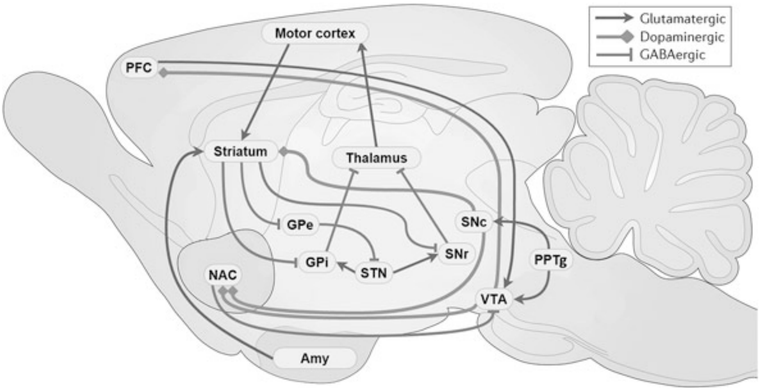

Fig. 2 Simplified diagram of the dopamine system of a rat brain, based on [4]. *SNc* substantia nigra pars compacta, *SNr* substantia nigra pars reticulata, *STN* subthalamic nucleus, *GPe* globus pallidus external, *GPi* globus pallidus internal, *Acb* nucleus accumbens, *VTA* ventral tegmental area, *PPTg* pedunculopontine tegmental nucleus, *Amy* amygdala

4 The Model and Simulation

We model the dopamine system of a rat brain based on [7, 9, 12]. The diagram presented on Fig. 2 depicts the dopaminergic nigrostriatal, mesolimbic and mesocortical pathways.

The direct pathway is: *Motor cortex* (stimulate) → *Striatum* (inhibit) → *complex SNr-GPi* (Thalamus is less inhibited) → *Thalamus* (stimulate) → *Motor cortex* (stimulate) → *muscles and* etc.

The indirect pathway is: *Motor cortex* (stimulate) → *Striatum* (inhibit) → *GPe* (STN is less inhibited) → *STN* (stimulate) → *complex SNr-GPi* (inhibit) → *Thalamus* (is less stimulated) → *Cerebral cortex* (is less stimulated) → *muscles and* etc.

We use NEST the Neural Simulation tool [3] to implement our model and perform the validation.[1]

SNc dopaminergic neurons and Glutamate neurons of Amygdala, they trigger the spikes starting from 400 ms till 600 ms, the period of the dopamine neuromodulation, spike detectors are installed in: the motor cortex, the prefrontal cortex, VTA, SNc, the thalamus see.

Starting from the 400th ms of the simulation modulating spike generators start firing: in amygdala excites striatum and acetylcholinergic and glutamatergic neurons of PPtg, that activate GABAergic neurons of VTA that project to PFC thus inhibiting it. Spike generators of PPtg and the amygdala remain active until 600th ms of our simulation.

[1]Project repository is available at https://github.com/research-team/NEUCOGAR.

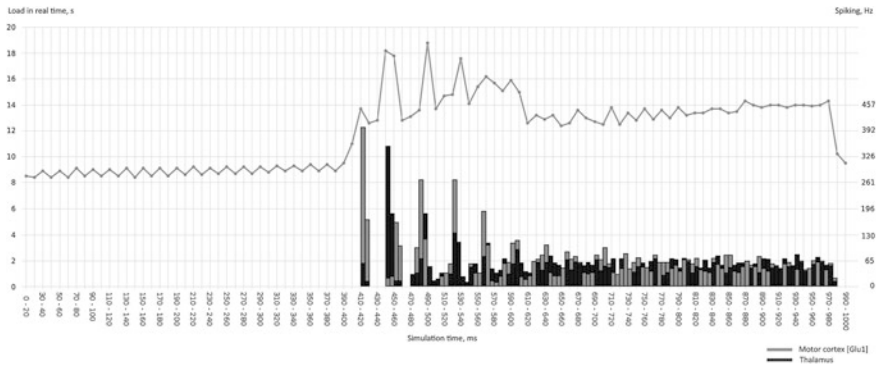

Fig. 3 The computational power used per 5 ms of simulation

4.1 Results

The overall duration of the simulation is 1000 ms. We register the neuronal activity every 0.1 ms. At the same time we register the computational power used to calculate every 10 ms of the simulation. The integrated graph is presented in Fig. 3. The **line graph** is the computational power used for the computation of the simulated dopamine subsystem of the rat brain with dopamine neuromodulation. Histogram depicts the frequency of spikes for: **light-grey**—Motor cortex, **dark-grey**—Thalamus. The computational power on the of Fig. 3 is represented in number of seconds used by the CPU on 100 % of utilization of the machine with running simulation.

The graph indicates the rise of the computational time per 5 ms of the simulation correlated with the rise of the dopamine neuromodulation of the simulation that matches the proposed hypothesis of the correlation of fear of a mammalian brain with the computational power consumed of a computational system.

5 Conclusions and Future Work

In this and previous works we propose that implementation of mechanisms similar to biological affects and emotions would correlate to computing system parameters of artificial systems. Dopaminergic, serotonergic and noradrenergic neuromodulation systems of mammalian brain create the neuronal mechanism of basic emotions according to the hypothesis of H. Lövheim. Our hypothesis is that we can map effect of emotions on mental processes to computation by reproduction of their mechanisms.

We had implemented a model of dopamine system of a rat brain using NEST Neural Simulation Tool and ran the validation via simulation of 1000 ms of dopamine neuromodulation inside of the model. The results indicate the increase of computational power exactly during neuromodulation. This can be understood as partial proof of our hypothesis along dopamine axis.

We plan further experimental validation and enhancement of proposed model, modeling and validation of serotonin and noradrenaline systems, their integration, validation of integrated system, development of appraisal models, and implementation in a working cognitive architecture.

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Spatial and Temporal Parameters of Eye Movements During Viewing of Affective Images

Olga Lomakina, Lubov Podladchikova, Dmitry Shaposhnikov and Tatiana Koltunova

Abstract Experimental results about the human eye movement parameters during free viewing of IAPS' images have been presented. For each subject (n = 20), the same positive, negative, and neutral images were presented. Each volunteer had similar scanpath during viewing of images with different valence. Coefficient of correlation (r) between number of tests with detected regions of interest at presentation of negative and positive images was equal to 0.84 (r = 0.80 between the tests with negative and neutral images, r = 0.77 between the tests with positive and neutral images). Similar correlation was revealed for fixation duration. Volunteer groups with dominant focal or scanning trajectories had significant differences in viewing area square, and fixation duration.

Keywords Affective images · IAPS · Focal and scanning viewing trajectories · Individual peculiarities of viewing · Viewing area square · Fixation duration

1 Introduction

It is well-known that eye movements during viewing of complex images depend on many factors, and are regulated by bottom-up and top-down mechanisms of visual attention [13, 17, 18]. One of the leading factors of such kind is emotional influence of an image on the man. Studying of various aspects of emotive perception point to the priority of affective images as compared with emotionally neutral stimuli [1–5, 7, 11, 14]. It was found [3] that affective stimuli primarily attract the attention of an observer, even if the instruction was given to view initially the neutral stimulus. In the studies, performed by combination of recording eye movements and tests on memorization and recognition, the activation of visual attention mechanisms since initial fixations during viewing of emotive images were revealed [7, 11]. It was

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shown the priority of emotional semantic features in attraction of visual attention over the primary visual features such as brightness, contrast [10, 11]. However, the parameters of viewing scanpaths while viewing of affective images were analyzed only in small number of studies [6, 9]. At the same time, it is necessary to study the dynamics of viewing trajectory structure, because it is considered as an important key to understand the visual attention mechanisms [12, 13, 18]. The individual differences of eye movements are often denoted, but without quantitative estimations of the individuality. In particular, it was described [1] the individual differences in the saccade amplitude and fixation duration. Thus, quantitative criteria for estimation of the dominant type of the visual attention of a particular person by eye movement parameters are unknown up to now [6, 16].

The results on individual characteristics of eye movement scanpath during viewing of images from International Affective Picture System, IAPS [8] with different emotional valence (positive, negative and neutral) have been presented in this paper.

2 Methods

20 volunteers (the average age is 21.6 ± 5.2) participated in these experiments. All subjects had normal or corrected-to-normal acuity of vision. The Bioethics Committee of SFedU approved experimental protocol. Each volunteer signed the agreement to participate in experiment.

In IAPS database [2, 8] each image was ranged in the nine-point scales of valence and arousal using a large sample of subjects. We used the following images with characteristic values of valence [2, 8] for each type of IAPS emotive images: 10 positive (№: 2216, 4250, 4607, 4689, 5470, 5621, 7279, 8158, 8190, 8499; the average valence: 7.35 ± 0.22; the arousal: 6.38 ± 0.22); 10 negative (№: 1101, 1300, 1303, 3101, 3185, 6350, 6370, 9140, 9908, 9941; the valence: 3.42 ± 0.31; the arousal: 5.79 ± 0.26) and 10 neutral (№: 2320, 2480, 5740, 7041, 7161, 7179, 7205, 7700, 7705, 9360; the valence: 4.87 ± 0.14; the arousal: 2.67 ± 0.06). Each image was presented during 6 s, gray mask was presented between the images during 1 s.

Eye movements were recorded by SMI iView X Hi-Speed eye-tracker with frame rate of 1250 Hz. The distance between subject's eyes and computer stimulus screen was 50 cm. Frame rate of stimulus monitor (NEC MultiSync LCD 1990Sxi) is equal to 60 Hz, monitor resolution is equal to 1280 × 1024 px. Saccades and gaze fixations were detected by the iView X and by home-made program implemented by EventIDE software (http://okazolab.com/). Image viewing was conducted binocularly, but movement recording was carried out for dominant eye only. The threshold of eye movement velocity was chosen as 40°/s. Statistical analysis was performed by BeGaze software and R: A Language and Environment for Statistical Computing (http://www.R-project.org). Differences between particular samples of data were evaluated by the Wilcoxon signed-rank test and the Student *t*-test.

3 Results

For each subject, a type viewing scanpath was evaluated according to the probability of detection of regions of interest (ROI) at the presentation of ten images of each type, i.e. negative, neutral and positive ones. ROIs were identified by estimation of spatial distribution of fixation points by the modified method of the nearest neighbor [12]. In all sample of subjects, it is found that the probability (p) of tests in which the ROIs were identified at presentation positive images were more as compared to the negative ones (p = 0.58, n = 194 and p = 0.52, n = 197, correspondingly). Besides, the coefficient of variation of this parameter between the subjects was also greater during viewing the positive images (61 and 51 %, correspondingly).

The distribution of probabilities (p) of tests with detected ROIs for all sample of volunteers (n = 20), and images (n = 30) is shown in Fig. 1a. On the base of described above results, the histogram is ordered according to the results obtained during viewing of emotionally positive images, from the maximum values of p to its minimum values. For each subject are also presented the values of p in tests with the presentation of emotionally negative and neutral images. The significant correlation ($p < 0.001$.), estimated by Pearson correlation coefficient, between the probabilities of tests with detected ROIs in the whole sample of subjects was found in three combinations of the tests: between negative and positive images, negative and neutral, positive and neutral ones (r = 0.84, 0.78 and 0.77, correspondingly). A similar correlation was revealed for fixation duration, in the same combinations of tests and in the same subject' sample (r = 0.90, 0.82; 0.90, correspondingly, for data presented in Fig. 1b). However a significant correlation between the distribution of probabilities of tests with the detected ROIs and fixation duration for the same volunteers hasn't been revealed. So, the coefficient of correlation between the distributions of these parameters was very low (r = −0.06, −0.15 and −0.31, correspondingly).

Two polar groups of the subjects were separated for further analysis in accordance with the results obtained at presentation of positive images: (1) with a dominance of the focal scanpaths (ROIs were detected in 80 % of tests, and more, 6 subjects); (2) with a dominance of the scanning trajectories (ROIs were identified in less than 40 % of tests, 6 subjects). The examples of viewing areas for the two subjects with the dominance of focal (subject Isk.) and scanning (subject Mak.) trajectories are presented in Fig. 2. It is evident that type of the scanpath is similar for each volunteer during viewing of images with different emotional valence.

Several types of analysis have been carried out for quantitative comparison of the subjects with the dominance of the focal and scanning trajectories. The square of viewing area [15] was determined in each test as a part of the image inside the contour figure (Fig. 2) that formed by the outside fixation points. It is calculated as a percentage from whole square of an image. Significant differences ($p < 0.05$) estimated by Student t-test between the subjects with the dominance of the focal and scanning trajectories are marked by symbol * in Table 1.

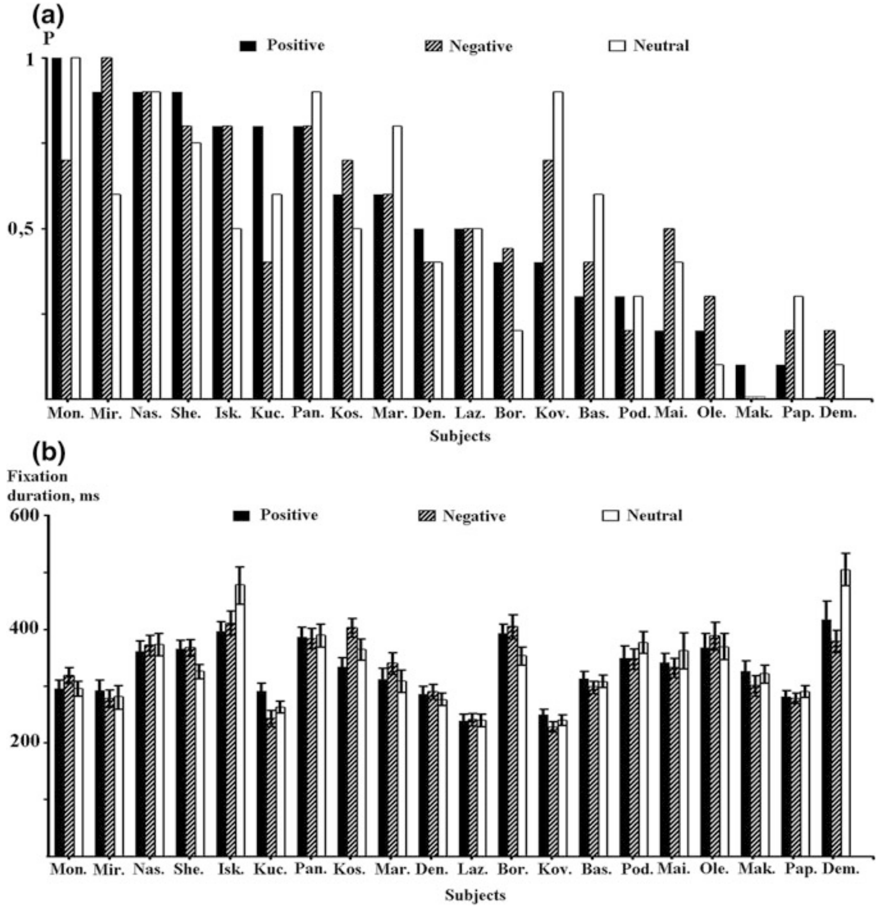

Fig. 1 **a** The distribution of probability (p) of tests, in which ROIs were identified during viewing of ten images of each type for all subjects. **b** The distribution of the average fixation duration for the same subjects. Standard error denotes by vertical stripe in each column

4 Discussion

The main results of this study are as follows: (a) significant correlation between the probability of tests with the detected ROIs was revealed in three combinations of tests: between negative and positive images, negative and neutral, positive and neutral ones in the whole sample of subjects; (b) similar correlation was found for the fixations duration; (c) described parameters of eye movements (probability of tests with the detected ROIs, the square of viewing area, and fixation duration) are significantly different between the two polar groups of subjects (with the dominance of the focal or scanning viewing trajectories).

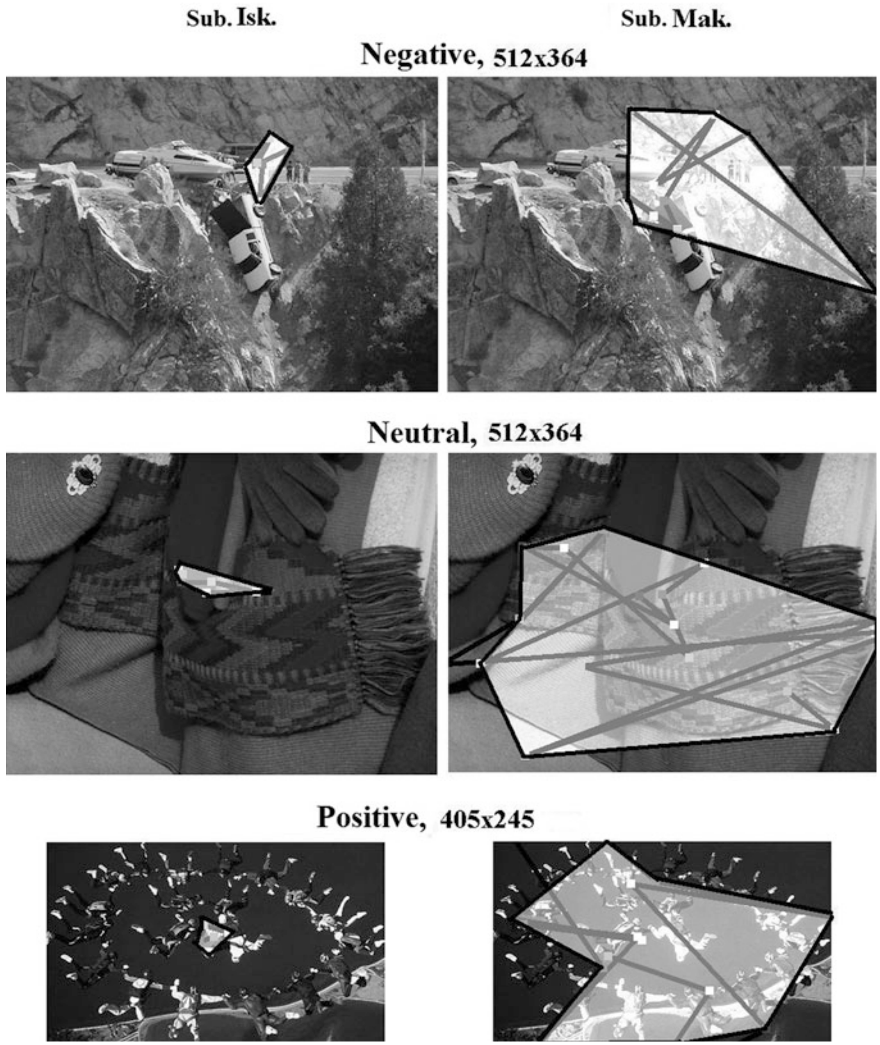

Fig. 2 Examples of viewing areas (*light contour figure*) of negative, neutral and positive images for two subjects. Image size indicates over each image

Our results about individual peculiarities of viewing scanpath may be compared with the known data. In particular, similar differences in scanpath structure between the polar groups of the subjects were revealed during viewing of complex images at qualitative level [12]. Besides, it was shown that the variability of eye movement parameters between the subjects was higher than the variability for the same subject [6]. It is interest to note the tendency to more pronounced individual differences of viewing scanpaths by a set of parameters used in our study at presentation of emotionally positive images. This fact is in agreement known data [1, 14].

Table 1 Viewing area square and fixation duration for the subjects with dominance of focal and scanning trajectories at presentation of positive, negative and neutral images

Parameters	Image type	Viewing trajectory type	
		Focal	Scanning
Viewing area square, % from square of whole image	Positive*	6.9 ± 1.3	27 ± 4.2
	Negative*	6.1 ± 1.0	25 ± 3.9
	Neutral*	6.6 ± 1.0	25.4 ± 4.0
Fixation duration, ms	Positive*	352 ± 14	315 ± 12
	Negative	347 ± 13	321 ± 12
	Neutral	356 ± 16	330 ± 12

The results obtained allow us to suggest that not only the type of the viewing scanpath (the focal or scanning ones) can be individualizing parameter for quantitative estimation of the dominant type of the visual attention of a particular person but also the fixation duration (see Fig. 1b and Table 1). The absence of a significant correlation between these parameters may be due to the different, but agreed mechanisms of the regulation of saccade amplitude and fixation duration [12, 17].

Present study can be considered as the primary realization of the approach to quantitative evaluation of the dominant type of the visual attention for a particular person by eye movement parameters. In future the detailed experimental studies will be carried out to estimate the range of variations of the revealed phenomena in dependence on various factors such as the semantic features of an image, motivation, and the current functional state of a person. Certainly, the individual characteristics of the viewing scanpath should be also formalized in mathematical models as an additional tool [10, 16] to study the dynamics of the mechanisms of the human visual attention during the viewing of complex images. At present, we are developing the new version of our biologically inspired model [12, 15] to imitate the temporal dynamics of viewing scanpath structure for polar groups of volunteers.

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MEG Data Analysis Using the Empirical Mode Decomposition Method

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Abstract In the present paper, we propose to use the method of Empirical Mode Decomposition for frequency band analysis of MEG data. This method is compared with the more traditional methods of narrow band filtering and Hilbert transform. By the analysis of MEG data recorded during subjects' volitional sensorimotor tasks, it is shown that the extraction of empirical modes can potentially detect some useful information about brain cognitive activity which is inaccessible to classical methods of frequency band analysis.

Keywords MEG · Empirical mode decomposition · Hilbert–huang transform · Frequency band analysis

1 Introduction

Up to date, the most popular ways of time-frequency analysis of neurophysiological data (in particular, EEG and MEG signals) are short-time Fourier transform, wavelet analysis, and narrow-band filtering with subsequent Hilbert transform [1]. In [2], it was shown that in theory these approaches are equivalent, however in practice for neurophysiological data analysis wavelet transform or Hilbert transform are usually selected [3]. Specificity of the first two approaches is a priory assignment of basis functions used in spectral decomposition—sine and cosine functions

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in case of Fourier transform and scaled wavelet functions in case of wavelet transform. Also, as a result of applying these functions, interference effects are possible that mistakenly could be recognized as frequency modulation. When Hilbert transform is used, a frequency range and narrow-band filter parameters have to be a priory defined. In this work, another method of time-frequency analysis of signals is considered namely Empirical Mode Decomposition (EMD) [4]. The EMD method is relatively new in digital signal processing, but it has already successfully proved oneself in different applications [5–7] especially in analysis of significantly nonstationary signals including analysis of neurophysiological data [3, 8]. According to results of several studies, EMD method outperforms wavelet analysis in the context of time-frequency resolution; also, this method does not require choosing of the basis functions [9, 10]. One of the goals of time-frequency analysis of neurophysiological data is to study phase synchronization of different brain areas or large scale brain networks. The results of time-frequency analysis are used in calculation of such parameters as coherence, Phase Locking Value (PLV), Phase Lag Index (PLI) and others [11]. In [12], it was proposed to use the EMD method in a task of reconstruction of brain activity sources; in [13], authors describe studies of spectral properties of intrinsic mode functions (IMF, a result of applying the EMD method [4]) and their relation to the number of available time samples based on real physiological data. In [14], a method was proposed to estimate properties of phase synchronization of EEG based on the EMD method. In that article, in particular, it was shown on model data that in a number of cases the usage of narrow-band Butterworth filtering with the Hilbert transform does not allow to find out phase synchronization presented in the original model signals. In the same time, in [14], it was shown that the EMD method is more effective than narrow-band filtering because it allows extraction of only those internal oscillations that are actually present in the analyzed signal. The EMD method was used for brain-computer interfaces [15] and for analysis of resting state neural networks on fMRI data. In the present paper we propose to use the EMD method for time-frequency analysis of MEG data. We reconstruct the Hilbert–Huang spectrum for MEG data recorded during volitional sensorimotor actions performed by human subjects and compare the spectrum with the Hilbert spectrum of filtered data. We hypothesize that the Hilbert–Huang spectrum can potentially reveal features not present in the classical Hilbert spectrum or avoid false results that are not proper for brain neural networks and that probably appear due to “imposing” particular frequency ranges during calculation or due to interference.

2 Materials and Methods

Magnetic fields generated by brain electric activity were recorded using 306 channel helmet-shaped array of magnetoencephalography detectors composing 102 identical triple blocks of sensors. Each block of sensors is composed of two flat orthogonal gradiometers and one magnetometer connected to multi-SQUID (superconducting quantum interference device) detectors and thus gives three independent measurements of magnetic field. In this study the results were recorded using 204 flat gradiometers because they provide optimal signal to noise ratio for surface current sources [16]. During the experiment, a healthy subject performed a task: raise the index finger of the right hand spontaneously once in 2 s. Four electrodes of electrooculogram (EOG) were used to record horizontal and vertical eye movements. EOG signals were recorded with a high pass filter of 0.1 Hz. Movement of the index finger was continuously recorded using three axis accelerometer attached to the dorsum of the index finger. MEG signals were recorded at sampling rate of 1000 Hz and filtered with a band pass filter from 0.03 to 330 Hz. The data were recorded on 24 healthy right-handed volunteers: 14 women and 10 men aged 20–33 years (mean = 25, SD = 4). The data were cleaned from artifacts and distortions. In order to slice the signal onto epochs, using accelerometer data, we added timestamps to the MEG signal aligned with the beginning of the finger movement (increase of the actogram signal). As a result, for each subject, 120 ± 20 time epochs were defined in the range of −600 to 600 ms beginning from each timestamp. The interval from −600 to −200 ms is considered as a pre-movement baseline range, and the interval from 0 to 400 ms is considered as an epoch of activity of interest related to the finger raise. In order to remove noise, epochs having the mean value of the signal out of range of ±3σ were removed from subsequent analysis. As a result, for each subject, 90 ± 10 epochs were used.

At first, we determined maximum of brain activity during motor actions. The maximum of the ERP is observed in MEG0432 and MEG0443 channels (placed close to the representation of the right hand in the sensorimotor cortex of the left hemisphere). For subsequent analysis we used MEG0443 channel. The algorithm of the EMD method is thoroughly described in [4]. Figure 1 (*left*) shows extracted IMFs in channel MEG0443 for one of the epochs. The intrinsic mode functions were extracted for each epoch; and in the working interval from 0 to 400 ms the value of spectral power density was calculated for each function. Figure 1 (*right*) shows plots of the spectral power density versus frequency for the IMF2 (maximum at 102 Hz), IMF3 (30 Hz), IMF4 (14 Hz), and IMF5 (6 Hz) averaged by epochs.

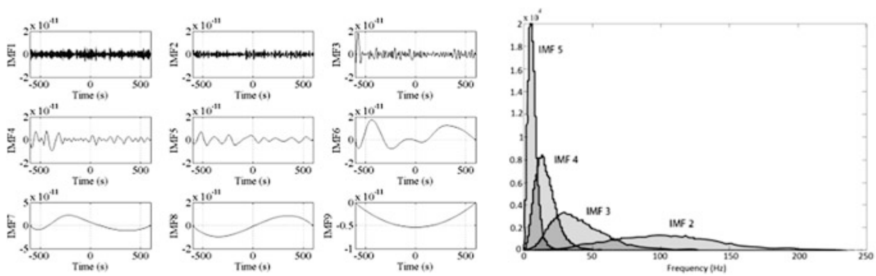

Fig. 1 Intrinsic mode functions on MEG0443 channel for one of the epochs (*left*). Plots of spectral power density versus frequency for the IMFs (*right*)

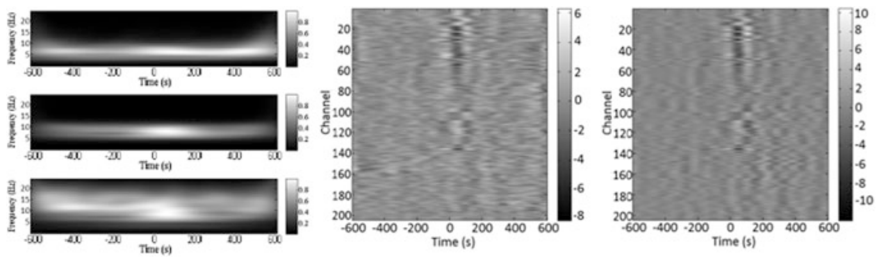

Fig. 2 Wavelet spectrums of the IMF5 (*upper left*) and the original signal filtered in frequency bands of 2–10 Hz (*middle left*) and 0–20 Hz (*lower left*). T-values of the IMF5 levels comparing to the baseline (*center*) and T-values the original data filtered in the range of 2–10 Hz comparing to the baseline (*right*)

The frequency ranges of IMFs overlap. In a separate study we determined that time-frequency behavior of IMF differs in general from the behavior of the source signal filtered in corresponding range. As an example, Fig. 2 (*upper left*) shows wavelet spectrums of IMF5 and the source signal filtered in frequency ranges corresponding to this IMF—2–10 Hz (*middle left*) and wider 0–20 Hz (*lower left*). So, it is seen that IMF extraction is not equivalent to simple frequency filtering of the source signal and potentially can reveal useful information, which can be missed by classical methods of time-frequency analysis. We compared averaged (by epochs) values of IMFs with the baseline using two-sample T-test applied to each channel (Fig. 2, *center*). The first sample is composed of IMF values in a particular channel and in a given moment of time. The second sample is composed of mean values (in the interval from −600 to −200 ms) in the same channel. Also, for a comparison, T-test was applied to data filtered in the frequency range corresponding to the selected IMF (2–10 Hz) (Fig. 2, *right*).

As a preliminary result, we applied the IMF values to calculate the weighted Phase Lag Index (wPLI) [17]. We calculated wPLI for several channels that showed high values in T-tests and ERP. Both filtered data and IMF based wPLI for MEG0443 sensor (that has the highest amplitude of ERP and located in the area of interest) show a slight decreasing tendency during motor action execution. The results for other sensors vary significantly and their analysis is the subject for future work. The wPLI index for the MEG0443 sensor shows coherence with higher number of sensors if calculated with the filtered data than with the EMD method.

3 Discussion

In this work, the EMD method was applied to analysis of MEG data recorded during volitional sensorimotor actions performed by subjects. It was shown that the results of applying the EMD method slightly differ from classical methods of time-frequency analysis, which can potentially reveal some new information. In particular, it was found that the highest difference of IMF5 mode and the baseline according to T-test was observed for channels MEG0122, MEG0132, MEG0413, MEG0422, MEG0423, and MEG1623 in time interval 30–60 ms starting from the beginning of the movement while for filtered data the highest difference was observed on channels MEG0413, MEG0422, MEG0423, and MEG0443 in time interval 30–100 ms. However, in general, this method gives less contrast images (which can be determined either by less sensitivity of the method or by its resistivity to false results). T-values of the IMF5 levels comparing to the baseline are slightly lower than T-values of the original data filtered in the range of 2–10 Hz comparing to the baseline. One possible reason for this effect can be the control of IMF and the filtered signal dynamics by different brain neural networks. Both filtered data and IMF show slightly higher inter-sensor wPLI coherence for MEG0443 channel in pre-movement time samples what probably reflects the need for synchronization of neural networks for action planning and for subsequent selection of effector neural networks involved in action implementation. But the result is inconsistent as the wPLI index based on other channels behaves differently. The wPLI index also shows coherence on higher number of electrodes if calculated with filtered data than if calculated with the EMD method. In the next step we plan applying the EMD method to calculate phase synchronization of MEG data for larger number of sensors and in particular for the source space.

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Evolutional Approach to Image Processing on the Example of Microsections

Tatyana Martynenko, Maksim Privalov and Aleksandr Sekirin

Abstract The new approach is proposed to color image processing and segmentation on basis of evolutionary models. The set of objective functions was developed for the estimation of segmentation quality depending on the type of histological research. Experimental research was conducted on the example of histological images. Obtained results showed the efficiency of the developed evolutionary processing and segmentation algorithms.

Keywords Image processing · Recognition · Evolutionary algorithm · Genetic algorithm · Segmentation · Cancer · Microsections

1 Introduction

Computer aided image processing systems (CAIPS) are used in many areas of science and engineering in order to find the solution the solution of such problems, as face image recognition, medical and technical diagnostics, text recognition, the systems of safety, etc. CAIPS application allows substantially accelerate the visual information processing, increase authenticity of objects analysis and recognition.

The medical images processing is one of the most important technologies where the study of color images obtained by any digital microscope is of particular interest. It is due to large amount of histological analysis in connection with the high percentage of oncological illnesses that are the second most frequent causes of death in developed countries. The successful treatment of cancer depends largely on

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early diagnosis and choice of treatment method. Therefore the main challenge is an early diagnosis of cancerous tumors and the discrimination between malignant from healthy structure and degree of malignancy.

The research of tumors is mandatory histological examination of atypical cell structures. Presently morphologists fulfill the analysis of microsections images manually. And a conclusion about the presence of one or another malignantness signs considerably depends on a doctor-morphologists skills and proficiency. Computer image processing allows you to make a more objective assessment of the images to improve the accuracy of established diagnosis and the speed of information processing. Existent computer systems of cells image analysis work with visually well-allocated structures. Many of known systems operate in the hand mode and have a high cost.

Automation of microsections morphology analysis allows to increase the authenticity of finding out the changes of internals under oncologic diseases and to accelerate the microsections image processing. Moreover it extends possibilities of prophylaxis and prevention of malignancies. However, the difficulty of obtaining high quality histological preparations and high variability of most of the histological structures were not allowed to develop an effective approach to the treatment and recognition of images of histological sections in the diagnosis of cancer till nowadays. Therefore, in spite of the obtained results, the task of microsections image processing and recognition is relevant.

2 Images of Histological Sections

The fragments of the images of histological sections of lymph node and gland, subjected to immunohistochemical staining, are shown in Fig. 1. On the images represented in Fig. 1 cells kernels reacted with colorant—positive cells (marked on a picture the sign of "+" are painted in a brown color, negative "−"—in dark blue).

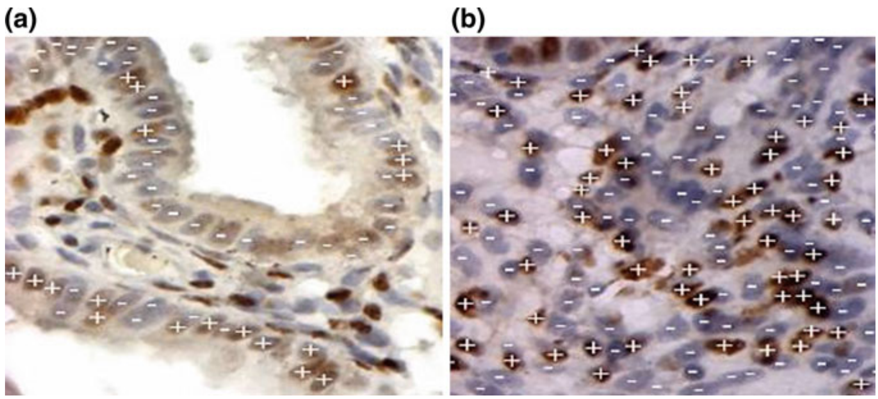

Fig. 1 The fragment of microsection stroma image: **a** gland; **b** stroma

The analysis of the represented images shows the weak brightness of negative cells, closeness of negative cells brightness with a background and other elements of histological image. Also we can see overlay of positive and negative nucleus images, belonging to different layers. Moreover, the element recognition depends on the context.

The analysis of the existent CAIPS shows that in spite of presence of a large enough number of the medical images processing systems [3, 5, 15], their functional possibilities do not possess sufficient efficiency because of the following factors:

- lack of universal methods of image processing, segmentation and recognition [6, 7, 12, 16, 17];
- lack of the criteria of efficiency estimation for the processing and classification systems of medical images;
- lack of effective methods and procedures of classification [6, 7, 12, 17].

Modern models, algorithms and computer-aided system often use the manual parameter tuning and heuristic algorithms for image processing that, as a rule, results in a loss of quality and adequacy of analysis [1, 2, 4, 6, 7, 16]. Therefore, in spite of the modern numerous researches, the problem of color images processing and segmentation remains relevant, especially it relates to adaptive methods. To overcome these drawbacks a modification of the evolutionary approach was developed to construct effective algorithms for processing images of histological sections [8, 13].

The modern image processing and analysis computer-aided systems for microsections must extract cell nucleuses, evaluate its dimension and shape, and, in some situations, its context. For these purposes it is necessary:

- to develop the methods of image preprocessing and contour extracting;
- to design the recognition methods for corresponding objects;
- to determine the object features;
- to develop the recognition methods for histological objects (positive and negative cells, gland etc.);
- to carry out the experiments that validate the proposed models and methods.

Basically, the paper represents the problem of cell nucleus extracting in the color microsections images that is solved on the base of evolutionary approach.

3 Segmentation Problem for Color Images

In general case the segmentation task is a partition of finite plane set into k nonempty connected subsets Q_i ($i = [1, k]$). For all that the function of initial image $f(x, y)$ is determined on the finite plane set, and partitioning is fulfilled according to some predicate P determined on the set Q = {Q_1, Q_2, …, Q_k} and taking on truth values, when any pair of points from every subset of Q_i satisfies the chosen criterion of homogeneity (for example, the criterion of maximal closeness of brightness of each individual pixel and the average brightness value, calculated on the proper area).

The input image of I_k is exposed to segmentation by the program S with the set of parameters P^s_j. We have the set of images M^s_{kj} as a result:

$$M^S_{kj} = \mathrm{segm}\left(S,\, P^S_j,\, I_k\right) \tag{1}$$

Quality of segmentation process is determined by the estimation of objective function (OF) of F, which can be calculated by different ways depending on the specific type of histological research.

The task of effective image processing and segmentation algorithm synthesis comes to generation of such processing operators sequence with the proper parameters values which gives the quality estimation maximum criterion for some image type. Processing accuracy is defined by evaluating the objective function F, which is determined by comparing of the segmented image M_k with the image from the training set G_l.

To solve this problem a step-by-step image processing procedure is proposed:

$$M_n = \mathrm{operate}\left(S_{i_n}, P^{S_{i_n}}, N_n\right), \tag{2}$$

where M_n is an intermediate image on n the processing stage;

S_{i_n} image processing operation (IPO);
P^S set of IPO parameters values;
n number of image processing operation;
i IPO number from the set of available operators;
N_n is a set of intermediate images, obtained at previous steps where the image M_n is built on the basis of:

$$N_n = \left(n_1, n_2, \ldots, n_{z(S_{i_n})}\right). \tag{3}$$

It is well known that more full color model will provide more effective segmentation procedure. So it is suggested to present an input image as a set of color planes:

$$I = \{C, R, G, \mathrm{Blue}, H, \mathrm{Light}, S, L, a, b, u, v\}. \tag{4}$$

Each color plane contains the values of the image pixels in one of color schemes (CM): RGB, HLS, Lab и Luv.

So, first 12 color planes are fixed:

$$\begin{array}{lll} M_0 = C; & M_1 = R; & M_2 = G; \\ M_3 = \text{Blue}; & M_4 = H; & M_5 = \text{Light}; \\ M_6 = S; & M_7 = L; & M_8 = a; \\ M_9 = b; & M_{10} = u; & M_{11} = v. \end{array} \tag{5}$$

Thus, to solve the problem it is enough to apply to one of the color planes these two steps:

$$M_{12} = \text{operate}(\text{ClipLo},(\text{CL}),(\text{field})), \tag{6}$$

$$M_{13} = \text{operate}(\text{ClipHi},(\text{CH}),(12)), \tag{7}$$

where *ClipLo* is a threshold limitation operation, where all pixels with values of CM with the number *field* (*field* $\in \{0, 1, 2, \ldots, 11\}$) below than parameter value *CL* ($CL \in [0\ldots255]$), set to 0, other take on the 1 values;

ClipHi—all pixel values, which exceed the parameter value *CH* ($CH \in [0\ldots255]$), set to 0, other to 1.

As result of above mentioned operations we obtain the binary image M_{13}.

4 Evolutionary Approach to Segmentation

Solving the problem using an evolutionary approach it is necessary to define [9, 10, 12, 14]: (1) encoding of potential solution (chromosome); (2) genetic operators of crossover and mutation; (3) fitness-function which allows to estimate quality of decision; (4) general evolutionary algorithm of task solving.

As potential solutions (chromosomes) it is proposed to use a directed acyclic graph, where internal nodes are the standard images processing operators, end terminals—outputs, and input nodes—the input image planes, we use as the representation of potential solution (chromosomes). It allows to describe practically any image processing algorithm, which is the sequence of standard operators. Functional and terminal sets, crossover and mutation problem-oriented operators were developed in [8, 11, 13]. The crossover operator is performed by the exchange of graph paternal individuals fragments, which is executed with using the rules set [8, 13]. The mutation is usually performed by the random change of this graph [8, 9, 13]. The algorithm is based on the concept of learning and uses a training sample. The essence of the method lies in reduction of the image processing algorithm to the artificial population evolution process of potential decisions, which gives a minimum error on a training set. Further we will consider the basic moments, first of all the creation of fitness-function for the images of microsections.

5 Fitness-Function for the Microsections Images

Structure of chromosome—potential solution searching for rational parameters values of the microsections colored images segmentation, it is suggested to present by following string:

$$\mathrm{Chr_i} = [\mathrm{field}, \mathrm{CL}, \mathrm{CH}]. \quad (8)$$

The segmentation result is a set of image homogeneous areas, comparable on accuracy with the results of expert visual analysis. A fitness-function must compare the processed image to the image from a training set (attributed to the certain class). The successful completion criterion of segmentation stage can be a proximity of the results of the method of segmentation and reference partitioning carried out by the human expert manually. In this case, the fitness function can be chosen to be any degree of proximity between the template g and the processed image h (for example, inversion of some metric, such as Hamming relative distance):

$$\mathrm{f_A} = 1 - \frac{1}{\mathrm{MN}} \sum_{\mathrm{i}=1}^{\mathrm{N}} \sum_{\mathrm{j}=1}^{\mathrm{M}} |\mathrm{h(i,j)} - \mathrm{g(i,j)}|, \quad (9)$$

where h and g two digital images with the size of M × N.

Obviously, the function f_A takes on a maximal value $f_A = 1$ under the complete coincidence of two images, and minimum value $f_A = 0$ under the complete lack of two images coincidence.

The function f_A depends on the number of coinciding images pixels only and can be used as the criterion for successful segmentation. It helps to consider the best match of pixels of the image. However, if the amount of pixels of one class considerably differs from the amount of pixels of another class, then using Hamming distance as fitness-function can give the contradictory results.

We will show it on the example of grey image segmentation (Fig. 2a). For this purpose, using relative Hamming distance, we will compare the reference pattern (Fig. 2b) that is obtained by expert. On Fig. 2 we can see different values of threshold segmentation results (Fig. 2c, d). In the first case a display element is not selected at all, than in the second—selected with the improper value of threshold. Hamming distance for both cases is equal to 0.92, however obviously, that in first case result of segmentation is far more optimal than second.

In that case, when the area of image element considerably differs from the area of background, the use of Hamming relative distance as a fitness-function can lead to contradictory results. To overcome the identified contradictions in such cases it is advisable to use a fitness-function, offered in [17]:

$$\mathrm{f_B} = 1 - \frac{\sqrt{(1-\mathrm{SP})^2 + (1-\mathrm{SV})^2}}{\sqrt{2}}, \quad (10)$$

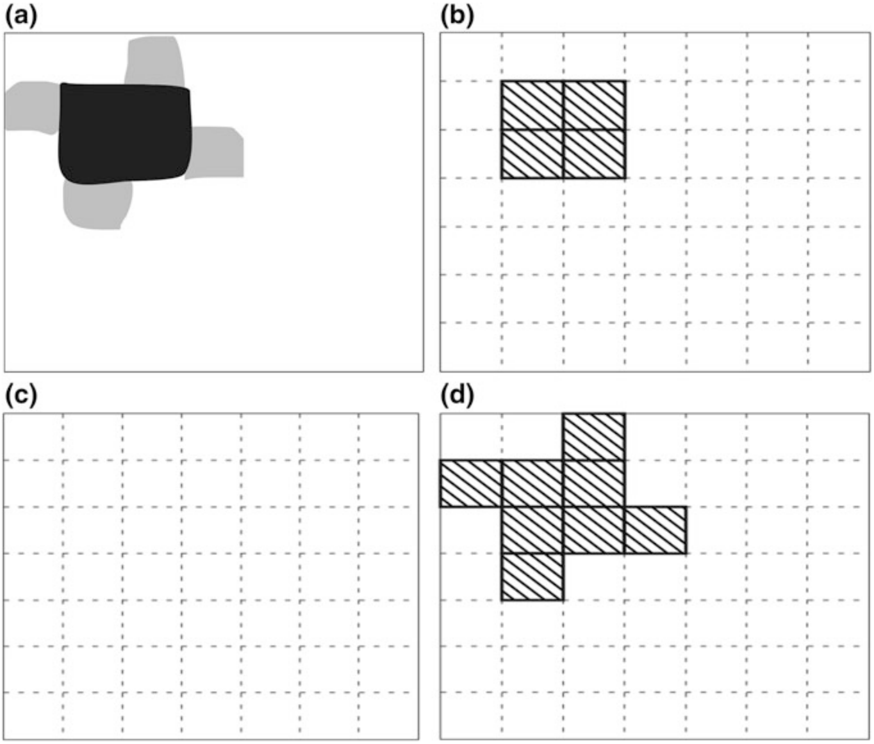

Fig. 2 Example of image segmentation: **a** initial image; **b** reference pattern; **c** result of segmentation 1; **d** result of segmentation 2

where

$$SV = \frac{card(\{(i,j)|h(i,j) = 1\&g(i,j) = 1\})}{card(\{(i,j)|h(i,j) = 1\})}, \quad (11)$$

$$SP = \frac{card(\{(i,j)|h(i,j) = 0\&g(i,j) = 0\})}{card(\{(i,j)|h(i,j) = 0\})}. \quad (12)$$

Variables SV and SP are a sensitiveness and specificity, accordingly [17].

Unlike the f_A function f_B depends on the amount of the correctly classified pixels, related to the background and to the image element. Optimum value of $f_B = 1$, when SP = SV = 1 (the closer SP and SV to 1 the must be value of function f_B closer to 1). Otherwise $f_B = 0$, when SP = SV = 0.

In some cases, it is helpful to assess two types of possible errors that arise during segmentation: missing or incorrect selection of element. So, if a positive cell with own characteristics is similar to the background then preferably it is a mistake to select a cell as cancerous, than to interpret the fragment as a background. Therefore there is a need to carry out adjustment of bias search error depending on the sensitiveness and specificity values.

For the removal of the indicated failing we propose the following fitness-function:

$$f_C = 1 - \frac{\sqrt{(1-(SP \times (1-\alpha)))^2 + (1-(SV \times \alpha))^2}}{\sqrt{8}}, \tag{13}$$

where $\alpha \in [0; 1]$ allows to carry out adjustment of bias search error depending on the greatest sensitiveness (high value α, nearby 1) and from the greatest specificity (low value α, nearby 0).

6 Structure of the System Tools' Software Implementation

The developed program system has a modular construction and consists of the followings main subsystems:

– image processing;
– selection of effective segmentation parameters;
– generation of effective microsections images processing and segmentation algorithms.

Block "Images processing" is the basic mode, where image processing depends on the type of histological research according to the calculated parameters values or synthesized algorithm.

Block "Selection of effective segmentation parameters"—carries out the calculation of segmentation parameters by the modified genetic algorithm. Before calculations the input of training and test images sets is fulfilled.

Block "The construction of the efficient algorithms"—carries out the construction of effective microsections images processing and segmentation algorithms with help of the developed evolutionary program. Before implementation of evolutionary process the training and test images are entered. The resulting screenshot of construction of effective processing and segmentation algorithms of lymphatic node microsection image is presented on a Fig. 3.

The developed program system is approved on the base of Pathology-Anatomic Ward of the Donetsk Regional Clinical Territorial Medical Association. The results of the experiments for determination of the developed modified fitness-function f_C efficiency and rational parameters values of evolutional process are represented on Fig. 4.

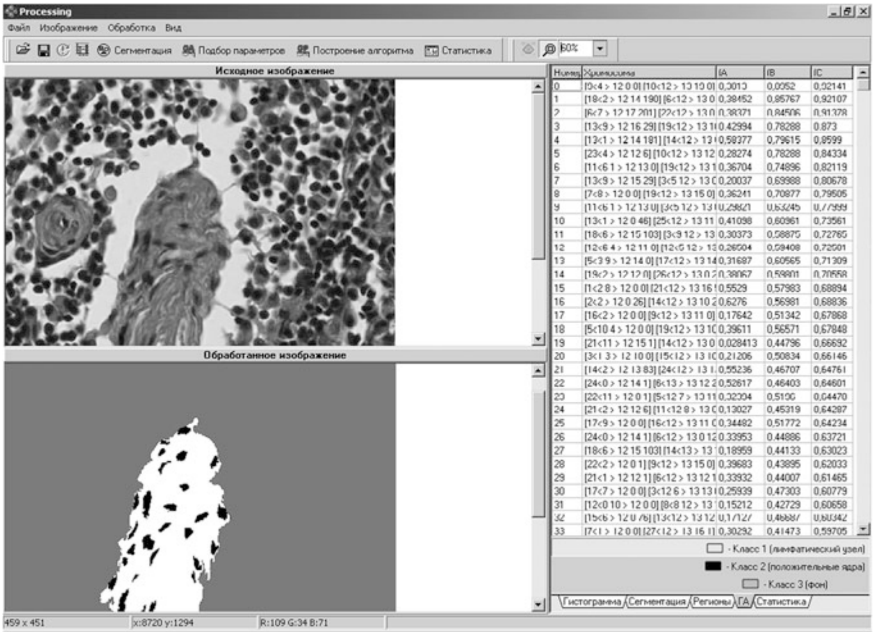

Fig. 3 The results screen shot of construction of effective processing and segmentation algorithms of lymphatic node microsection image

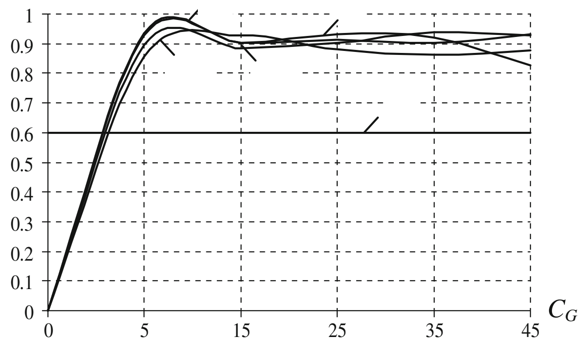

Fig. 4 Dependence of fitness-function f_C on the amount of generations (C_G) and power of population: *1* or 25 chromosomes; *2* for 50 chromosomes; *3* for 75 chromosomes; *4* for 100 chromosomes; *5* is a decision, got by the k-average method

7 Conclusion

The new approach to color images processing and segmentation on the basis of evolutionary models is proposed. Experimental researches on the example of microsections images confirmed efficiency of the suggested processing and segmentation algorithms with the use of evolutionary approach.

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"Cognovisor" for the Human Brain: Towards Mapping of Thought Processes by a Combination of fMRI and Eye-Tracking

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Abstract The aim of this work was to describe localization of active brain of different types of thinking—spatial and verbal. The method of functional magnetic resonance imaging (fMRI) was used. Seven right-handed healthy volunteers aged from 19 to 30 participated in the experiment. In the experiment, the subject was brought against 6 types of tasks (about 30 of each type) distributed from the figurative to the semantic thought. The results obtained in the statistical parametric and covariance analysis is that interactions of neural networks that are activated to perform the categorization of mental tasks are different. This makes it possible to use this approach to develop a model of "Cognovisor".

Keywords fMRI · Cognovisor · Cognitive space · Eye tracking · SPM · EEG

1 Introduction

Today the idea of revealing the structure of cognition by means of the objective brain signal measurement remained to be topical. As those signals, fMRI and EEG were the major candidates. A series of works devoted to fMRI signatures of perception appeared in 1990s and 2000s. Haxby et al. [1] observed patterns of activation in Ventral temporal cortex that coded perception of different categories of

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perceived stimuli: faces, chairs, shoes, and buildings. By calculating the correlation coefficient between current activation pattern and the previously obtained average activation pattern it happened to be possible to detect a category of the stimulus being perceived with an accuracy of more than 95 %. Pietrini et al. [2] further developed this result showing that not only visual stimuli categorization was possible with fMRI but also tactile stimuli as well. Shinkareva et al. [3] performed similar research, in which perception of tools and dwellings was discriminated with fMRI signal. It was found that performing mental tasks in mind are accompanied with an establishment of certain patterns of EEG rhythms [4].

It occurred that "cognitive" patterns of EEG rhythms are in certain relations with each other, and that those relations may be disclosed and visualized if a metrics in a space of EEG patters is introduced. To introduce a metrics means to specify a procedure that calculates distances between patterns of EEG rhythms. This procedure may be based on statistical comparison of EEG Fourier spectra, for example, as it is accomplished in [7]. After the distances are measured, we may plot different cognitive conditions on a surface (in most simple case, on a plane) in a manner that preserves the measured distances as close as possible. As a result, we obtain a "map of a cognitive space" for a given person. Surprisingly, individual maps of cognitive space revealed to be similar, which means that those maps are relatively invariant of individuality. This fact made it possible to obtain the average map of cognitive space, as revealed with EEG signal analysis. Simultaneously, we asked experts to evaluate the degree of psychological properties of different kinds of mental activity used in the experiment (e.g., degree of the involvement of spatial, verbal, and imaginative thinking). After mapping the obtained scores, we got the maps of the subjective evaluation of the mental activity types. The "subjective" (experts' questioning) and "objective" (EEG measurement) maps of cognitive space coincided with great accuracy. This implies, in turn, that informational processes in the brain are supported and coded by EEG rhythms.

The main disadvantage of the EEG approach to "objective mapping of cognition" resides in the properties of the EEG signal itself. The signal is indirect and highly blurred and integrated. In contrast to EEG, fMRI method consistently shows much greater stability and less between-subject variability. The procedure of construction of a cognitive space map, as described earlier for EEG, is also suitable for fMRI signal. We may calculate distances between patterns of BOLD signal corresponding to different mental conditions. This gives us distance values, which we can use exactly in a way we did with EEG. There may be a variety of ways to calculate distances between different patterns of a BOLD signal.

2 Materials and Methods

For presentation of visual and audio stimuli in the MR scanner during functional studies we used a projection-system. Presentation software (Neurobehavioral Systems, USA) was used for paradigm development. To register the subject's eye movements EyeLink2000 eye tracker was used with the following parameters: active method of pupil registration (Purkene); sampling rate = 1000 Hz; accuracy of eye deflection angle detection = 0.5°. Permission to run the experiment was obtained in ethics committee of INHA RAS. The experiment was conducted on the MRI Magnetom Verio 3T residing in the NRC “Kurchatov Institute”. Seven right-handed healthy volunteers aged from 19 to 30 participated in the experiment. Experimental data were obtained using echo planar sequence with the following parameters TR = 2000 ms, TE = 25, voxel size $2 \times 2 \times 2$ mm^3 for BOLD imaging and TR = 1900 ms, TE = 2.21 ms and voxel size $1 \times 1 \times 1$ mm^3 for structural MRI. During the experiment, there was a simultaneous recording of fMRI, EEG and eye movement data (eye-tracking). To register subject’s responses we used Current Design system, consisting of two panels (with 2 buttons) for the left and right hands. Thus, to complete the task the subject had to choose a response with one of the four buttons. In the experiment, the subject was brought against 6 types of tasks (about 30 of each type) distributed from the figurative to the semantic thought (Fig. 1).

The sequence of presented stimuli was formed via random number generator. Once a sequence has been generated it was used for all subjects. Having solved the task, the subject pressed the button for the correct answer. For decision of each task it was given 16 s.

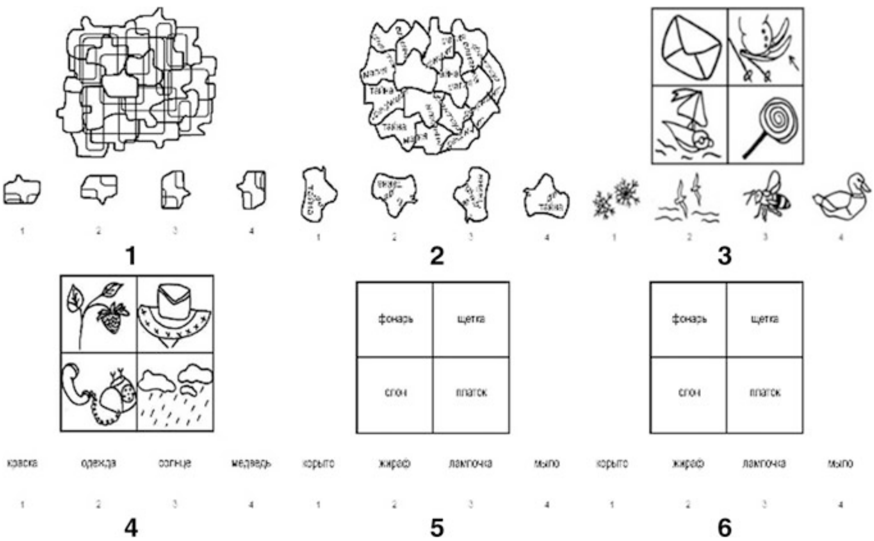

Fig. 1 Examples of presented tasks: **a** of the four proposed options pick an element of the puzzle, suitable for shape and pattern on it (S1); **b** of the four proposed options pick an element of the puzzle, suitable for shape and words on it (S2); **c** of the four options choose a picture logically wrong to represented in one of four squares (V1); **d** of the four options choose word logically wrong to represented pictures in one of four squares (V2); **e** of the four options choose specific word logically wrong to represented in one of four squares (V3); **f** of the four options choose abstract word logically wrong to represented in one of four squares (V4)

fMRI data preprocessing was performed using SPM8 software package Structural and functional data were put to a center in the anterior commissure. Images were normalized to template images (T1-template for structural and EPI template for functional) with 2 × 2 × 2 mm^3 voxel size in MNI (Montreal neurological institute) coordinate system. fMRI data were corrected for magnetic field inhomogeneity. Functional data were coregistered to the structural data. For noise and effects due to residual differences in functional data reduction we smoothed it with a Gaussian kernel of 8 × 8 × 8 mm^3 width. For paradigm design construction we used moments of stimulus as an onset for GLM, and the time for subject's answer (pressing a button) as a duration. Time corresponding to resting state was accepted as time between subject's answer and the beginning of stimulus.

3 Results

We used T and F statistics for comparing different stimuli to achieve high significance of our results. It was received 42 statistical maps (for each condition comparison) for each subject. During this analysis, there was no statistically significant changes in the BOLD signal when comparing S1 and S2 tasks. We believe that the lack of significant differences when comparing the conditions S1 and S2 due to the low number of correct answers, which in turn may speak about difficulties with these stimuli perception. Figure 2 shows the percentage of correct answers in the tasks for each subject. According to our calculations mean response times for all tasks were comparable with each other (about 10 s).

The second stage of the experimental data processing included calculation of covariance matrices between the different regions of the brain, involved to address the mental tasks. Brain volume was divided into 136 anatomical regions (a modified AAL atlas). Covariance analysis was performed between all this regions at the group level for the each contrast, selected in the previous processing step. As a result, two covariance matrices were calculated for each selected contrast.

First covariance matrix displays zone which has a maximum reliable and extensive activation obtained by the results of the first analysis—BOLD-signal increase during task with respect to the rest (Fig. 3), the second matrix shows the functional connections through Occipital Fusiform Gyrus right (Fig. 4) at various mental tasks. Occipital Fusiform Gyrus right here given as an example, since the

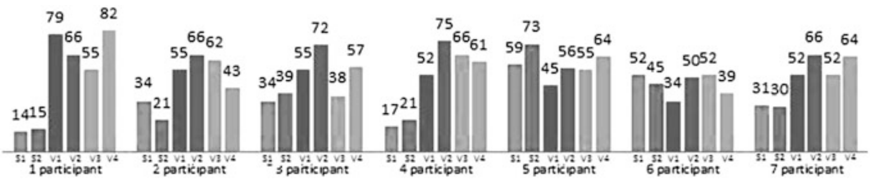

Fig. 2 The percentage of correct answers in the tasks for each subject, %

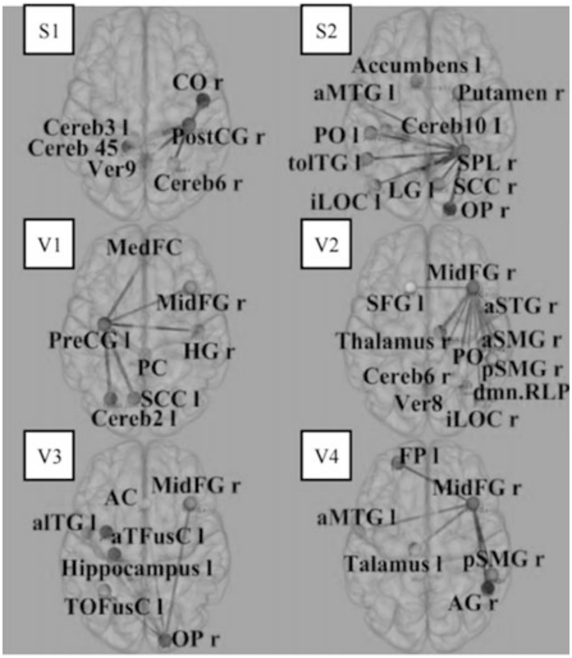

Fig. 3 Covariance connections of most active zones in each mental condition (designated by numbers). The significance level $p < 0.05$

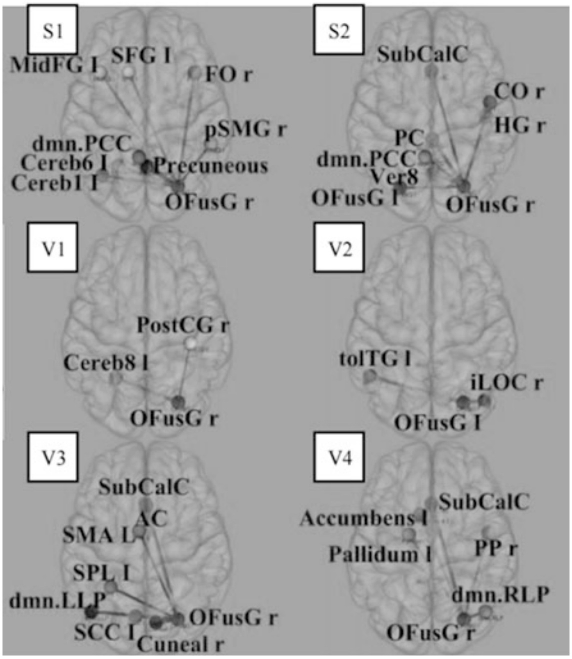

Fig. 4 Statistical analysis of fMRI data for the group of subjects by Occipital Fusiform Gyrus right area correlation. Significance level $p < 0.05$

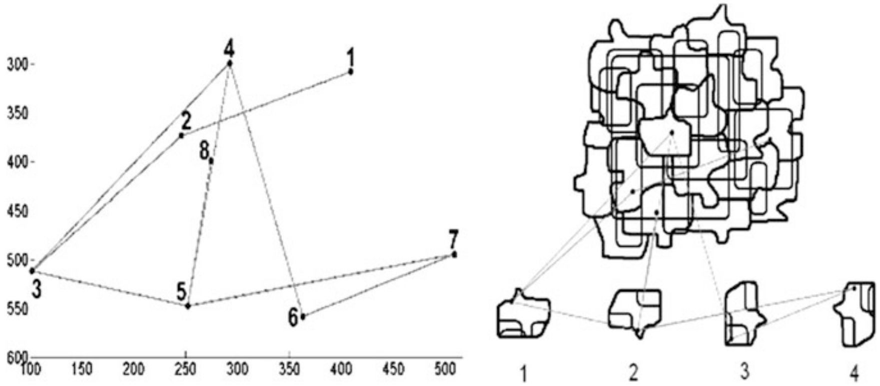

Fig. 5 Example of states extraction based on track of the eye movements. *Left* 8 selected states for the first type of tasks (S1), *right* imposition of tracks per picture S1

results of the first analysis were reliably shown to be involved in brain activity when performing all 6 types of tasks. Since eye movements were recorded during the experiment subject's, Fig. 5 shows an example of the registered track view. All data were classified to a different number of states. The states with the highest frequency were identified as areas of maximum attention for solving problems. These conditions are planned to be used as a regressor in the next step of fMRI data processing.

4 Disscussion

The conclusion that can be drawn from the results obtained in the statistical parametric and covariance analysis is that interactions of neural networks that are activated to perform the categorization of mental tasks are different. This makes it possible to use this approach to develop a model of "Cognovisor". The presented results were obtained using time as a regression for the fMRI signal.

Conclusion on the part of the work associated with the processing of eye tracking data: additional information obtained using eye movement data allows to classify the types of shown tasks and their solutions. This data could be used as a regressor for defining microstates brain using fMRI data analysis. Here, we come to a point when we put forward a new idea of a "cognovisor", i.e. a technology of monitoring mental activity in real time and in a cognitive space. This new technology is, actually, a combination of two methods that we already have in EEG and that, we hope, we'll have in fMRI in the near future. These methods are: (a) recognition of the on-going mental activity in real time based on the analysis of unique patterns of brain activity (ether EEG or BOLD signal); and (b) construction of a cognitive space map based on the measurement of the distances between patterns of brain activities. In practice, the "cognovisor" works as follows. On the first step, the cognitive space map is constructed using some preliminary data. On the second stage, distances between the ongoing brain activity and reference activities used to construct a cognitive space are calculated in real time. Based on these calculations, we define a "work point of cognition" that travels across the cognitive map, showing the current state of person's cognition.

A great advantage of a "cognovisor" based on fMRI is that we can directly see brain areas activated in different mental states. An EEG "cognovisor" is faster (and cheaper). Combination of both methods supplies the advantages of both. A new technology promises to be practically useful; it can be applied in the fields of psychiatry, general and professional education, and much on. In the next phase of work in the processing of MRI regressor will use the power spectrum of the simultaneously recorded EEG signal, and durations of fixations defined by MR-compatible eye tracking data analyses. There will also be an attempt to find a metric vector which will allow combining the spaces obtained by the EEG, fMRI and the psychophysiology.

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Dynamic Intelligent Systems Integration and Evolution of Intelligent Control Systems Architectures

Victor M. Rybin, Galina V. Rybina and Sergey S. Parondzhanov

Abstract The work deals with the problems of integration and hybridization in today's dynamic intelligent systems. On the example of the individual classes of intelligent control systems (ICS) development experience the evolution of ICS architectures in accordance with the integration paradigm of artificial intelligence with models, methods and tools from other areas (automatic control system, simulation, etc.) are examined. An example of the integration of complex discrete systems simulation models with of dynamic integrated expert systems separate components developed in MEPhI and based on task-oriented methodology and tool set AT-TECHNOLOGY is described.

Keywords Integration processes · Dynamic intelligent systems · Intelligent control systems · Integrated expert systems · Task-oriented methodology · Simulation modeling

1 Introduction

In the current circumstances, the establishment of the vast number of applied intelligent systems for real practical significance and complexity problems requires close integration paradigm of artificial intelligence (AI) with a variety of methods, approaches and technologies from other areas. It is the most prominent feature of the current AI state and computational sciences related with the technological complexity of the software industry and the transition of enterprises and organizations from partial automation to the complex. Efficient and competitive operation of modern enterprises and companies in an ever-increasing complexity of tasks and fast changing demands of consumers today is largely determined by the possibilities

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of joint use of intelligent systems, powerful methods of system analysis and methods of artificial intelligence, mathematics and productive logical-linguistic models and research methods, as well as holistic design methodologies and associated tools to support the development, as shown in [14, 17].

As a consequence of the integration process emerged a wide range of issues-specific and subject-specific applications of intelligent systems, the specificity of which is completely determined by the orientation of specific tasks models and methods or various subject areas specific representations. Entirely new classes of integrated intelligent systems architecture has emerged where, along with traditional AI components such as simple expert systems (ES) appeared DBMS (database), packages of applied software of settlement and graphic nature, learning systems of different typology, CAD subsystems, separate automatic control classes, simulation tools, and so on [14, 15, 17].

Hybridization ideas (usually within one paradigm), which appeared in the AI a long time ago, have also received a new development in the context of the integration process. But the actual practical implementation of this idea, in particular the establishment of the neuro-expert systems, combining neural network techniques and search patterns with ES mechanisms, based on the logical-linguistic (expert) knowledge representation models and models of human reasoning, was only possible thanks to modern platforms and IS type NeurOn-Line (Gensym Corp) [6]. Overall, however, the theory of hybridization AI is just developing, despite some theoretical research and successful implementation, e.g. [1, 7, 24].

Thus, may be stated that at the turn of XX and XXI centuries, a trend towards the integration of research in various fields has appeared most clearly, which has led to the need to combine semantically different objects, models, methodologies, concepts and technologies. This has generated a diverse range of software architectures of applied intelligent systems for which there is no semantic unification of terms used and a single universal classification, and the most systematic studies of integration processes, and examples of integration architectures of intelligent systems contained in the three-volume monograph [18–20].

Particular importance in modern conditions acquire a dynamic intelligent systems (DIS) as a result of the AI methods and means integration with the classical methods used in traditional dynamic systems, such as automatic control systems, simulation and others [18–20].

It should be noted that certain classes of DIS, in particular the dynamic ES, including operating in real-time (RTES), already have a long history of research and development from the earliest dynamic ES and ES RT mid-1980s the last century.

A detailed review of these systems is contained, for example in [3, 5, 11, 30]. A more complex class DIS—dynamic integrated expert systems (IES) started developing since the late 1990s including IES based on the use of the task-oriented methodology in static and dynamic areas of concern (ABM) [14].

Around the same time the other DIS classes have started actively development. They are intelligent decision support system (IDSS), for example [31] and multi-agent systems (MAS) [33]. At the beginning of the XXI century, the peak of popularity fallen to the new DIS class—Intelligent Control Systems (ICS) of technical objects and processes based on the automatic control of software and hardware systems self-purposeful behavior [8, 9, 32], and others.

The architecture of the ISU and the evolutionary development on the basis of integration processes from classical regulators to ICS based on dynamic IES MAC is in the focus of this work and are given the scope of practical application and high growth rates.

2 Intelligent Control: The Evolution of Approaches to Building Intelligent Control Systems

Researches and developers are engaged in intelligent control and the creation of relevant intelligent control systems (ICS) for more than 40 years. Starting around 80th years of the 20th century, models, methods and tools traditionally related to the field of artificial intelligence (AI) have started to be actively used in management theory and practice. In addition, hardware and software development included in the automatic control systems (ACS) came to be called intelligent components (modules) of these control systems [8, 9, 12, 16, 32].

Because objectives and methods of automatic control theory was developing and evolving almost simultaneously with the objectives and methods of AI, the related integration processes could not help but form a new area of scientific knowledge at the junction of these disciplines—intelligent control. Some earlier works, in particular RAS academician Vasiliev [32], has also used the term “intellektnoe upravleniye”, which is more likely due to the lack of uniform interpretation of English phrase intelligent control, which is often translated as “intellektualnoye upravleniye”.

Despite the discrepancy of points of view on what is currently understood by intelligent control, a significant proportion of authors agrees that, in general, the intelligent control meant automatic control of autonomous purposeful behavior of software and hardware systems [8, 9].

Under the intelligent control system (Intelligent Control System—ICS), in accordance with [12, 16], are meant systems in where during the formation of control actions in the control loop are used the information processing apparatus constructed using currently available. In theory of automatic control, classical synthesis procedure of the control device (controller) typically includes such steps as: establishment of a mathematical model of the control object (differential, difference and integral equations, frequency characteristics, etc.); development of requirements for the functioning of automatic control system (ACS) as a whole; development of architecture, composition, structure and parameters of the regulators (in the form of analytical dependences) [12, 16].

However, in actual practice, especially when creating control systems of complex technical systems (CTS) [14, 19] and distributed applications, such a scheme is difficult to implement due to the fact that: it is impossible to construct an accurate mathematical model of the CTS; there are additional sources of external disturbances, such as the so-called operational parameters in control systems of the electro physical complexes [14, 18, 24], etc., which are difficult to take into consideration because of their instability and uncertainty; user requirements for the developed CTS are inconsistent, incomplete, approximate, etc.

Intelligent control ideas, such as [8, 9, 12, 16, 32] et al., involve the construction of a new generation of ACS, based on the use of models, methods and techniques of AI. They also presume the rejection of the necessity of building accurate mathematical models objects and the “hard” formation of control actions algorithms, as well as including in the intelligent ACS such functions as decision making, planning behavior, learning and self-learning in the conditions of dynamic problem area.

To date there have been offered a lot of different approaches for the construction of the ICS (fuzzy information processing, and soft computing, neural network techniques, evolutionary modeling, multi-agent systems, etc.), but the greatest progress has been made using the methods of knowledge engineering and the creation of ICS based on the expert real-time systems (RTES) [31] and dynamic integrated expert systems (IES) technology [14, 18, 19].

The following summarizes the implementation features of ICS architectures certain types based on methods and means of DIS.

3 Modern Architecture Intelligent Control System

Currently a common view on the architecture of a typical ICS has not been developed. The most common point of view, for example, [12, 16] is linked with the presence of a ICS layered architecture on the lower levels of the hierarchy that uses formal models of conventional ACS, and the upper layers which provide processing incomplete and uncertain information associated with the analysis of external and internal situations, based on the use of classical AI techniques (logical conclusion, plausible reasoning, learning, knowledge processing with non-factors, etc.).

As noted above, the concentration of the ideas of intelligent control based on the integration of the traditional control theory and AI and the creation of a new generation of ACS with components that implement intelligent management, or even a full-featured ICS. This has currently most clearly manifested in the DIS [14, 19], their variety of architectures can be seen as a concrete result of the applied intelligent systems different typologies and level of difficulty with individual ACS classes integration.

That is why approaches to the creation of ICS are based on the integration of separate classes of DIS, in particular, the dynamic IES with traditional ACS. In this case using the technology of dynamic IES is due to the advanced management of dynamic systems by incorporating complex problems without the traditional analytic representation (or in which models in the form of dynamics equations are less efficient than models of AI), and the treatment of incomplete, uncertain, indistinct, etc. information containing non-factors of knowledge [14, 18].

The architectures of these systems are built, as a rule, based on the two-level dynamic models, where the one level of the models is associated with the strategies of behavior systems (often formed on the basis of unformalized tasks), and the other provides the implementation of specific mathematical models. Thus, at the top supervisory management level of the ICS there is information processing for such type of management tasks where an important role is played by expert judgment and knowledge of man, because dependencies in the models of the control object are so complex that they does not allow the correct mathematical formalization [12, 16].

As shown in [10, 14, 19, 26–29], the integration not only with the traditional ACS, but also with the methods and means of simulation CTS issues are also important in dynamic IES. Also including systems of this type in the architecture, the corresponding subsystems, adequately reflecting all the processes and laws of functioning simulated systems.

In ICS, the basis of intellectual control make research in planning behavior, i.e. intellectual abilities of system to synthesize sequence of actions to achieve the desired targeted outcome. To create effective methods for such synthesis besides classical planning methods of construction planners are being actively developed today, including intellectual [4, 9, 14] are involved the temporal (temporary) logic for controlling planning and describing time dependencies [18, 26–29].

On the other hand, increasing attention to the problems of distributed AI technology and multi-agent systems are caused by necessity of paralleling the search and processing of information in the ICS. In addition in the intelligent control systems the methods and means of interaction agents of various typology in multi-agent systems are quite promising [23].

Hybridization is also the main way to create optimal DIS architectures by integrating diverse models, methods, algorithms and procedures. Today hybrid architectures of intelligent agents and multi-agent systems are well-studied, and the greatest prospects in this area are associated with them, which is important for building modern ICS. Hybridization methods of dynamic IES with neural networks (neurocontrol), evolutionary methods and genetic modeling and other approaches used for the implementation of intelligent control brings a rather good result.

It should be noted that an effective means of implementing IMS based on dynamic IES is a tool system G2 (Gensym Corp.) [6]. Considerable experience has been gained in creating dynamic IES for management tasks of the CTS based on the use of this tool system, in particular, for the management of modern electro physical complex [14, 18].

A dynamic version of the Russian software tools AT-TECHNOLOGY that supports task-oriented methodology for building dynamic IES is being actively developing (described in [14, 18–21, 24, 25], and others.). It also presents the modern software of WorkBench type, including interconnected set of automation means to architecture, develop and support IES on all its life cycle stages.

4 Integration Features in ICS Based on the Dynamic IES Architecture

For building ICS based on dynamic IES architecture, i.e. IES using a subject domain dynamic presentation and solving dynamic problems, significant experience of using task-oriented methodology IES was collected, which was established in MEPhI by Rybina [14].

In the context of solving the modern IES construction problems (in particular for the management of complex discrete systems) task-oriented methodology has the following properties:

– a powerful combination method of acquiring knowledge that supports the automated process of acquiring knowledge from the sources of knowledge of different typology (experts, database, text) is used to gain knowledge [14, 18, 22];
– generalized knowledge representation language designed for building models of problem areas in dynamic IES allows to represent temporal knowledge, based on a modified interval Allen logic and time control logic, together with the basic knowledge, including those containing knowledge with uncertainty, imprecision and vagueness [13, 14, 18];
– supports the use of various output means (universal AT-SOLVER and a specialized temporal solver designed for dynamic tasks) [13, 14, 18];
– in the context of enhanced functionality and principles of the components IES deep integration provides the possibility of implementing simulation techniques for modeling the external environment and how to interact with them [14, 18, 24, 26–29];
– the high efficiency of the a large number of applied IES development, including dynamic areas of concern [14, 18–20, 24];
– instrumentally supported by a modern software such as WorkBench (complex AT-TECHNOLOGY) [14, 16, 18–21, 24, 25].

In the dynamic IES important place is given to the integration of methods and means of temporal information presentation and processing with the methods and means of the outside world simulation (in this case discrete CTS) in real time. This leads to expansion of ICS architecture, built on the concept of dynamic IES relevant subsystems adequately reflecting all the processes and laws of functioning simulated systems, as an integral phase of building dynamic IES. Using [14], lets take the example of an integration model components of simulation discrete CTS models in language RAOAT [18, 28, 29] with the other components of dynamic IES (Fig. 1).

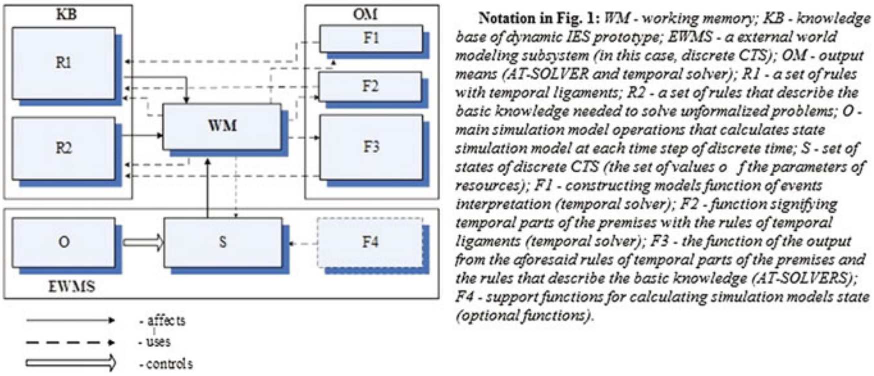

Fig. 1 Model component integration of simulation models in the RAOAT language with the other components of the dynamic IES

5 An Example of the Integration of Simulation Models of Complex Discrete Systems with Other Components of the Dynamic IES

Language RAOAT is used here for a description of discrete CTS simulation models. This language was developed on the basis of Russian method of RAO (Resources, Actions, Operations) [2], which allow to maximize fully reflect the behavior of any discrete type CTS (change of state resources, the emergence of regular and irregular events, and so on).

It is important that the description of the CTS resources and description of the objects in the problem areas of the developed language of knowledge representation are conceptually close, allowing the temporal solver at AT-TECHNOLOGY complex to use parameters of the resources from the simulation model of discrete CTS through the working memory in the temporal withdrawal. So are all the prerequisites for the integration of simulation technology with dynamic IES technology in today's ICS.

Model shown in Fig. 1 is interpreted as follows. The working memory discrete CTS simulation model resource settings are presented describing the state of the system that come into the working memory after calculating the new states of the simulation model on every step of discrete time. The calculation of the simulation model new state on every step of discrete time is realized by simulation model basic operations and functions of the F4.

Rules of the type R1 describe temporal knowledge (i.e. the knowledge that consider time as the subject domain nature). Functions F1 operate the resource settings in the current cycle and the interpretation model of events development in the previous cycle to modify the interpretation of the model development of events in the current cycle. Then function F2 provides valuation of the temporal parts assumptions of the rules type R1.

Functions of the F3 type operate with the parameters of resources represented in the working memory, the R1 type of rules and regulations with the indicated temporal parts of rules parcels. As a result, output of the temporal change of the system state rules occurs, i.e., in general, the attributes of the objects of the working memory change in accordance with the purpose of the problem being solved. The detailed description of the building IES tor intelligent control tasks theory and technology are presented in [11, 14, 19].

6 Conclusion

Thus, if until recently the formulation and solution of control problems in ACS was based on traditional mathematical models (for example, in the form of differential or finite-difference dynamics equations of the controlled process), then at the present time there is an active evolution of the objectives and control practices in the direction of intelligent control, and in particular, controlling technical systems. The most developed and advanced ICS here are implemented through the integration of traditional ACS and dynamic IES. The work was done with the Russian Foundation for Basic Research support (project 15-01-04696).

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Automated Planning: Usage for Integrated Expert Systems Construction

Galina V. Rybina and Yuri M. Blokhin

Abstract The problems of intellectualization in the development process of integrated expert systems basing on the problem-oriented methodology and the AT-TECHNOLOGY workbench are considered. The experience from carrying out intellectual planning for the synthesis of architectural layouts of prototypes in integrated expert systems, the intelligent planner usage, reusable components, typical project procedures, and other components of the intellectual software environment in the AT-TECHNOLOGY complex is described.

Keywords Artificial intelligence · Integrated expert systems · Problem-oriented methodology · Intelligent program environment · AT-TECHNOLOGY workbench · Automated planning

1 Introduction

The questions that are connected to intelligent assistance of the most labor intensive processes in the construction of an integrated expert systems (in particular, knowledge acquisition from knowledge sources of various typologies, management of projects and design automation, construction of intelligent tutoring systems, etc.) have always played an important role in the methodologies and technologies of various classes of intelligent systems.

Currently, these problems are particularly relevant in the conditions of the roughly emerging market for information technologies and a shift of emphasis towards so-called openness of systems, both for users, and for developers, since the factors of decrease in the cost indices of development and the intelligent load on knowledge engineers have become the most important requirements for methodologies and tools for constructing intelligent systems by strengthening the degree of intellectualization of the system construction at all stages of the lifecycle. These

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questions have a particularly important challenge for the automated support for the processes in the construction of integrated expert systems (IESs) [11], which have powerful functionality and scalable architecture.

The practical experience that has been accumulated during the creation of a variety of static, dynamic, and teaching IES usage based task-oriented methodologies and the instrumental AT-TECHNOLOGY complex, which supports these methodologies [11], has shown that the design and implementation stages of IESs still have the greatest complexity and the specifics of concrete problem areas and the human factor have significant impacts.

In this regard, the development of the intelligent software environment and its basic component, viz., the intelligent planner [11], to increase the process automation degree of project scheduling and controlling, which are related prototype IESs, is particularly vital in the context of the further development of problem-oriented methodology and the AT-TECHNOLOGY complex. Some versions of intelligent planners, which were developed on the basis of combining models and methods for intellectual planning with the methods that are traditionally used in IESs, have been created for the AT-TECHNOLOGY complex [11].

The focus of this work are the questions that are connected to the development of the intelligent planner and other components of the intelligent software environment in the AT-TECHNOLOGY complex, including on the basis of methods and means of automated planning; therefore, an important place is given to a detailed analysis of the current status of the research and development in the field of automated planning.

2 Analysis of Modern Methods and Intelligent Planning Software

2.1 Basic Terms and Approaches

Automated planning is often used to mean the automatic generation of plans for some hardware/software system [7, 8]. Respectively, a plan is some representation of future behavior in the context of intelligent planning; in particular, the plan is usually a set of actions with some restrictions (for example, temporal) for execution by some agent or agents [7]. A *planner* is practically unambiguously under stood as a software system that generates plans based on a formal description of the environment, the initial state of the environment, and objectives that are set by the planner. In some works, the planner is called an agent [8]. The scheduler which distributes resources for carrying out the constructed plans can be embedded into a planner, or can be an external component [7]. Now let us review in details the most modern and popular planning approaches.

Planning in the state space. This is classical approach for AI and based on a heuristic search, was successfully implemented in the well-known STRIPS system;

however, the revival of active interest in it is connected to the development of effective heuristic functions, i.e. hLM, hFF, and hCG, Reachability Heuristic and Planning Graph Heuristic [2] (based on GraphPlan). Currently, searching in the state space is the most popular approach in automated planning; in particular, the TFD/LAMA scheduler is implemented on its basis [9].

Temporal planning. In contrast to the classic planning, where a rather trivial model of time is used, such parameters as the duration of actions; parallelism of plans, resources, dynamics of change in the environment, and binding goals to time are considered in temporal planning [1] by the use of more complex models of time.

Planning in the non-deterministic and probabilistic areas. Interest in non-deterministic planning has occurred since the 1970s; however, it achieved new successes and results only in recent years. This approach allows us to simulate the problem areas in which it is impossible unambiguously to predict the behavior of a planning object as the probabilistic factors are used in events and actions. This can be carried out both on the basis of probabilistic networks and using fuzzy networks, which provoke the greatest interest among researchers. The PPDDL languages (Probabilistic Planning Domain Definition Language) and the Relational Dynamic Influence Diagram Language (RDDL), which replaced it, were developed for this direction.

There are also other approaches, which description can be found in the fundamental works [7, 8, 10]: planning using propositional logic; planning in the space of plans [8]; planning as a constraint-satisfaction problem; planning on the basis of precedents (Case-Based Planning); transformation to other tasks/problems [1]; hierarchical planning (HTN) [7].

2.2 *Formal and Conceptual Issues*

Here, it should be noted that a strict mathematical formulation of the problem of intellectual planning in the modern works is not given as a rule; however, the task is considered in the context of solving a planning problem in combination with specifically selected methods of AI, and most often, preference is given to the use of the methods of heuristic searching in the state space. The most general formulation of a planning problem can be found in [11] as $PlanTask = \langle E, G, A \rangle$, where E is a set of initial state, A is a set of actions and G is a goal.

In the modern foreign works planning task is defined base on the Labeled Transition System concept $\Sigma = \langle S, A, E, \gamma \rangle$, where S is a set of states, A—actions, E—events, and γ—transition function [7]. In general, the planning problem definitions that are used by various authors, rely on a basic set of the **following axioms**: finiteness of Σ; full observability Σ; the determinacy of Σ; statical Σ; the limitation of an objective; linearity of plans; implicit task of time; offline planning. The above axioms impose significant restrictions on formulating planning problem, and, respectively, a violation of the axioms complicates a planning task.

Use of the term *classical planning* as one of tops in the ontology is based mainly on planning in the systems in which all of the axioms listed above are carried out; this class of planning problems in the literature is often associated with STRIPS planning; STRIPS is an early system of planning for the Σ that are described above [7]. Temporal planning differs from the classical type in its more difficult model of time, namely, the duration of actions, admissible parallelism of actions, and others. In resource planning instead of Boolean variables there are real variables that provide the possibility of modeling more complex tasks. The nonidentity cost of actions is characteristic of planning with the cost of actions, although this representation can be generally modeled in resource planning. Planning with a partial constraint satisfaction is characterized by the partial description of objectives in contrast to the classical representation with the full certain target state. Non-deterministic planning allows partial uncertainty of both states and the results of actions and is currently the most dynamic model of planning.

In general, planning algorithms are based on the algorithms for searching on graphs, and the "intelligence" in planning is achieved through the use of special heuristic functions. The most popular algorithms are: A*, A* Best-First, Greedy Best-First, Eager Best-First, Lazy Best-First, Enforced Hill Climbing, Restarting Weighted A*, And/Or graph (AO*), Loops AO* (LAO*), Bidirectional LAO* (BLAO*), Reversed LAO* (RLAO*), Path Pruning A* (PPA*), which are widely described, for example in [10]. The heuristic functions are divided into admissible (A) and inadmissible (NA) and their difference is that the heuristic functions of the NA type can overestimate the real cost of a fragment of the optimum plan, which defines the transition between two specified states. Detailed heuristic and algorithm classification is given in [14].

2.3 Instrumental and Technological Issues

The PDDL language (Planning Domain Definition Language) [6], which has been developed under the leadership of McDemort and for which three main versions have already been created, is a peculiar language that is standard in the field of automated planning. It is possible to distinguish the following trends in the context of developing and using various formalisms of automated planning and corresponding languages: unification and standardization of planning languages on the basis of the PDDL language; the emergence of task specific planning languages; a shift in the emphasis of studies towards non-deterministic planning; and the emergence of mechanisms for the satisfaction of difficult preferences and restrictions.

We will list the most demanded and widespread automated planning languages and pay the main attention to methods that are little known in the Russian literature; however, these are widespread in the foreign developments. The main "classical planning" started from Situational Calculus, and then there were developed STRIPS, ADL, PDDL (Planning Domain Definition Language) with versions 1.0

and 1.2. The SAS and SAS+ encodings are widely used even today, and they are based on multivalue ask encoding. Some problem-specific languages were developed like OPT, NDDL, MAPL and APPL. For temporal planning problems PDDL 2.1, PDDL+, PDDL 2.2, PDDL 3.0 were developed. The nondeterministic planning languages are PPDDL and more modern RDDL. Detailed description can be found in [14].

2.4 Applied Issues

The methods and techniques of automated planning are used at the present time in a wide range of applications, the most valuable of which are briefly considered below [7, 14].

Controlling autonomous robots. Controlling robots is one of the traditional problems of automated planning. One of the most famous and successful foreign projects is controlling the Mars Rover [7], where the Mars Rover was operated by a planner based on the data from the various sensors of the Mars Rover. It is necessary to distinguish the works on the control of autonomous robots [18] among the Russian studies, in particular, calculating the optimal trajectory of unmanned aerial vehicles, which is a rather complex challenge, as it is necessary to consider many issues (for example, land relief, minimization of fuel consumption, dynamics of the environment, partial observability of the environment, etc.) basing on MT-graphs and the HGA* algorithm.

Biology and medical. Automated planning is successfully used in some biological problems key. The [17] is an example of using technologies associated with the tweezers operation, namely path-planning and image processing technologies applied to the operation of one single beam optical trap to manipulate biological cells automatically. With the path planning algorithm, the cells can be moved with avoidance of obstacles at the least movement cost, which ensures the efficiency and safety of manipulation. This allowed positioning of single cell and transportation of the cell with nanometer precision. In [16] is given an example of using automated planning for radio surgery treatment planning, which gives an improved conformity index, a higher minimum target dose, and a reduced volume of isodose line as compared to the corresponding plan developed by an experienced physician.

Logistics. Strengthening of the trend towards the use of the methods of automated planning, which the experience from the international IPC competitions of schedulers shows, is seen in the modern technologies of logistics infrastructure, as well as for modeling logistic networks, passenger transport, chains of deliveries, and other issues.

There are a lot of other interesting applications of automated planning, for example: web services composition in **semantic web**, individual computer-aided learning [5], equipment calibration, conveyor machine control [4], resource scheduling [3], knowledge engineering [15], resource scheduling in computational systems, automation of software development. It should be noted that, in general, their use for the purpose of the automated support during the processes of constructing intelligent systems is still a poorly studied area. This is mainly the experience that has been gained during the creation of applied IESs based on the task-oriented methodology and its supporting tools viz., the AT-TECHNOLOGY complex [11–13]. We will consider the basic concepts of the intelligent software environment in the AT-TECHNOLOGY complex in more detail.

3 The Generation of the Development Plan for an Applied IES Prototype

The task of creating the development plan of an applied IES prototype is a complete task from the field of AI, as it requires the involvement of very different knowledge about models and methods for solving typical problems [11], about the technology of the design and development of IESs, about methods of integration with databases and some applied programs, etc. Therefore, the set of knowledge and data on the solved task that is stored in some format on physical media and on the basis of which IESs prototyping is carried out under control of an intelligent planner is called a project to develop an IES on the basis of the problem-oriented methodology.

Significant place in the framework of the problem-oriented IES constructing methodology (basic points are reflected in [11]) is given to the methods and means of intelligent software support for the development processes. It is general concept of “intellectual environment”. Complete formal description of the intellectual environment model and methods of the individual components implementation is presented in [11], so here is only a brief description:

$$M_{AT} = \langle KB, K, P, TI \rangle \tag{1}$$

which includes a technological knowledge base (KB) on the composition of the project; a set of current project contexts; an intelligent planner that handles the development and IES testing process; a set of tools used at various stages of IES development. The main procedural (operational) component is intelligent planner:

$$P = \langle SK, AF, P_a, P_b, I, GP \rangle \tag{2}$$

containing the state of the current context; a set of functional modules; a selection procedure for the current target based on the global development plan; a selection procedure for the best executive function module from the list of possible candidates; procedures to ensure the interface with the corresponding components of the workbench; operating procedures for the IES global development plan. Brief descriptions of some of the main models are given according to [11] for the description of the basic processes of managing the development of an IES prototype, whose creation requires the use of certain types of knowledge and the use of an intelligent planner.

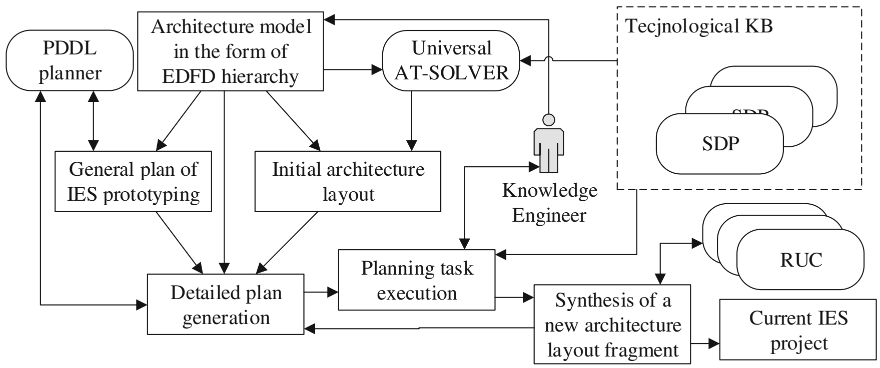

Fig. 1 Planning scenario

The development plan of an IES prototype, can be decomposed into global and detailed plans. The global plan consists of general development tasks basing on relationship to correspond to an architecture layout element which relates the elements from a set of tasks with the architecture layout components of an IES prototype from a PDFD, which is described as the hierarchy of the EDFD. It should be noted that the development of each component from the architecture model of an IES prototype is a complex process that can be described by a full network of specific tasks. The detailed plan is a specification of a global plan on the basis of an HTN formalism. The planning task of IES prototype development can be presented as a set of all available actions of the knowledge engineer over the project, initial and goal layout states. As it is shown in Fig. 1, the main task of the intelligent planner is dynamic support for the operations of the knowledge engineer at all LC stages of creating IES prototypes by generating the development plans of the current IES prototypes and providing the opportunities for concrete plans.

Since the planning task of the development of an IES prototype usually means an unambiguous out come of the performance of the planned tasks, deterministic planning was chosen as the main approach. This approach does not allow one to consider the events that are related to the risks and failures of the project due to the human factor in an explicit form; however, this is compensated by the restructuring of the plan strategy in the case of deviations from the plan. The environment for the planner, which is IES project description is entirely foreseeable. Planning is performed in the state space of the project, which is formed from possible values of project parameters. The choice of this approach is due to the popularity and the large number of planners that can be easily integrated into the intelligent planner.

In general, the plan to create an IES prototype is a complete task of project development; therefore, the elements of the plan need to be tied to the time, according to which the "temporal approach" with explicit modeling of time should be used. This allows the intelligent planner to adapt under the control of team development in the further studies, which is one more argument in favor of temporal planning.

4 Conclusion

An experimental program for the study of the current version of the intelligent scheduler is carried out during prototyping of teaching IESs for various courses/disciplines. It is planned to provide the abilities of the intelligent scheduler for use in the conditions of team prototype IESs with limited resources. In addition, the cycle of studies and development that are connected to implementing an intelligent scheduler and other components of an intelligent software environment for the creation of the software of two applied dynamic IESs has begun (Management of medical forces and resources in the case of major accidents and Resource management of satellite communication systems between regional centers). This work was supported by the Russian Foundation for Basic Research (project no. 15-01-04696).

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Features of Temporal Knowledge Acquisition and Representation in Dynamic Integrated Expert Systems

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Abstract We review the problems of the acquisition of temporal knowledge for the automated construction of knowledge base in dynamic integrated expert systems, the development of which is based on the task-oriented methodology and AT-TECHNOLOGY workbench. Analyze modern approaches of temporal knowledge acquisition from different sources of knowledge. And present features of the extended knowledge representation language and combined knowledge acquisition method, as well as promising directions of its development.

Keywords Artificial intelligence · Integrated expert systems · Task-oriented methodology · Temporal knowledge acquisition · Natural language processing · Combined knowledge acquisition method · AT-TECHNOLOGY workbench

1 Introduction

The problems of knowledge acquisition from sources of different typology (experts, natural language texts, databases), as well as problems of creating effective technologies of automated knowledge acquisition are still the focus of the development of modern intelligent systems, such as integrated expert systems (IES) with scalable architecture and extensible functionality [16, 22]. This important area of artificial intelligence is devoted a significant amount of research, widely represented in the fundamental papers, such as [6, 8, 18, 30] and others.

The analysis in [19, 22] showed that the most acute problem of knowledge acquisition arises in solving complex practical problems, particularly in fields such as medicine, energy, space, ecology and others, where it is not always enough to have just one expert. Therefore, to build the most complete and consistent models of problem domain (PD) and reduce the risk of experts mistakes, groups of experts should be involved, which significantly increases the cost of system development.

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Accordingly, it is increasing the relevance of processes automation and leads to the need of development of special software designed for computer-support of a process of knowledge acquisition from an expert or group of experts, which are the main source of knowledge.

In addition, typology of sources of knowledge is not limited to experts, since significant amounts of expertise accumulated in the natural language texts (NL-texts) and information accumulated in modern business information systems. Knowledge acquisition from NL-texts is associated with rapidly progressing technology—Text Mining [14], and automated knowledge extraction from databases devoted to areas such as Data Mining and Knowledge Discovery in Databases (KDD) [35]. Text Mining technology successes are related to the various aspects of the use of textual methods of acquiring knowledge from NL-texts that have greatly developed into the three types of modern web-oriented NL-systems—information retrieval, information extraction and text/message understanding [3, 11, 18, 22, 33].

Each of these technologies emerged and developed independently and today such autonomy does not allow to effectively maintain the information resources such as knowledge base (KB), database (DB), and in recent years ontologies. However, in addition to [19, 22, 24] there are no research on the development of tools and technologies of distributed knowledge acquisition from sources of different typology.

For example, as shown in [19], in order to overcome the problem of incomplete KB (situation where expert does not know and/or forgot to mention any fact required to solve the problem), you can proceed as follows: invite a specific expert more than one time; invite other expert or group of experts; use an independent source of knowledge in the form of a database. The first two methods can lead to the disruption of the whole process of PD modeling due to a substantial increase in the cost of labor of expert/experts, and as a consequence to the so-called "noise" personal characteristics of experts (a misunderstanding, omission, conformism, cognitive protection, lack of semantic unification of terms used and others) [18, 22].

Therefore, the most neutral and independent source of knowledge is a database. In particular, the analysis of experimental data obtained in process of developing knowledge bases using task-oriented methodology and AT-TECHNOLOGY workbench for a number of IES showed that local use of the database as an additional source of knowledge is able to replenish the amount of knowledge in KB for about 10–20 [16, 19, 22]. Thus, the benefits of automated knowledge acquisition technology, including knowledge distributed in various sources, are obvious. In accordance with conceptual basics of task-oriented methodology of developing IES [16, 19, 22] an integral part of this methodology is a combined knowledge acquisition method (CKAM) and automated technology of its use at the various stages of IES life cycle.

In the CKAM itself and instruments of its implementation a so-called *local* option of knowledge acquisition is considered [16, 19, 22]. However, after the transition to the web version of the AT-TECHNOLOGY workbench another option of automated knowledge acquisition has become available. *Distributed* method provides within a client-server architecture on the one hand, the integration of all the above types of knowledge sources, and on the other—taking into account their geographical distribution, as well as the opportunity to work with groups of distant sources of knowledge [21, 24].

Thus, using intelligent software technology and AT-TECHNOLOGY workbench—automated knowledge engineer workstation based on task-oriented methodology (including CKAM), a few dozen of static IES and the first prototypes of dynamic IES (which use dynamic representation of the PD and solve dynamic tasks) have been developed [16, 17, 20, 23].

For now research focused on one of the most important trends in the further development of task-oriented methodology and AT-TECHNOLOGY workbench, the scientific and technological problems of acquiring, representing and processing of temporal knowledge for developing dynamic IES. Series of works are dedicated to this issue [21, 22, 25–27], describing the results of developing models, methods and software.

2 Some Modern Approaches to Obtaining Temporal Knowledge from Different Sources of Knowledge

Despite the fact that the problem of knowledge acquisition (both with manual techniques and through the development of specialized tools that automate the processes of acquisition), is the basis of knowledge engineering in artificial intelligence, issues related to the temporal knowledge acquisition are still scarcely explored and discussed mainly in the context of automated processing of natural language texts, i.e. the extraction of temporal information (an example of such texts are reports, medical history, etc.).

Great success achieved in the class of systems of Information Retrieval (IR) and Information Extraction (IE), focused on the processing of English texts in electronic form. Such systems are mainly used in medicine and industrial sector for the collection of statistics from text documents (in medicine—history of the disease [32] and in the industrial sector, for example, processing of reports on breakdowns [10]).

In general, the construction of the temporal structure of NL-texts using different methods of semantic processing allows you to analyze large volumes of information stored in the form of NL-texts (reports, manuals, medical history, etc.) that pre-constitutes one of the topical task of developing a modern information about the space-knowledge. For example, since 2007 research group SIGLEX, a part of the Association of Computational linguistics, contests SemEval (Semantic Evaluation) for the best system of semantic analysis of NL-text.

Analysis of English papers on various issues of extracting temporal information from NL-texts, shows that despite the lack of a unified terminological database, extraction of temporal data is a set of processes of extraction of temporal entities—events and temporal markers and the process of establishing temporal connections (relations, dependencies) between the essences extracted from the text. As of the formalization of the information received (for example grammatical categories, expressing time in NL-texts, as a kind of time and verbs), these processes are directly linked to the explicit or implicit model of time. There are systems in particular [4], by which the extracted temporal dependence of NL-texts presented in terms of the formal theory of time, for example, the interval time theory [2].

In general, the development of instruments for automated extraction of temporal relations (connections) from NL-texts requires a deep involvement of linguistics experts, which is in the competence of the following tasks [12]:

1. To identify the temporal relationships in NL-texts there is a need to extract information about the events mentioned and pointers to specific intervals of time, and then analyze the relationships between them.
2. Retrieving the events require pre-designed ontology of events, as well as agreements about which segments of NL-text carry the largest amount of information about the event. The main problems are related to the inability to extract the required aspects of meanings of words, without resorting to deep semantic analysis, which complicates the process of relating extracted events with a particular class of ontology and makes determining their temporal properties difficult, as well as prevents the identification of the events expressed by parts of speech, distinctive from the verb. To solve these problems, various methods of machine learning (supervised and unsupervised) are used, particularly CRF (Conditional Random Field), maximum entropy, Markov logic networks and semantic-oriented language processing [18, 23].
3. While retrieving the temporal markers, in addition to the problem of determining the boundaries of the relevant text segments, there is a problem of bringing different types of pointers to a single kind, i.e. removing a normalized value of pointers. Here, first of these problems solved by the same methods as in the case of events, and the most effective method of normalization of indexes based on specialized sets of rules.
4. The process of establishing temporal relations are still the least successful since they depend on the results of the previous stages, and the choice of the appropriate theory of time formalization. Temporal logic (the theory of time) should allow to formalize the temporal aspects of events and temporal markers, as well as to describe a set of relations, which could then be easily operated. In dynamic IES solution of this problem is completely determined by used formalism of representation of temporal knowledge.

As shown in [26] the extraction of temporal information from the NL-texts in Russian further complicates all the above problems due to factors such as: large lexical diversity of ways of expression of time; the complexity of determining temporal relations between events (through a pre-decomposition); the presence of characteristic ambiguity of the Russian language, anaphoric references, etc. Thus, the task of extracting temporal information from NL-text is divided into three subtasks [15]: (1) list the relationship in a sentence; (2) search relations with the creation time of the document; (3) search relationship with neighboring sentences. Very different approaches and techniques can be applied to these subtasks: machine learning neural networks [9, 31], ontology construction and the search for the graph concepts [29], Markov logic [36], consideration of the syntax and semantics of a particular language.

In addition, some methods (in particular related to machine learning) based on the use of a large corpus of problem-oriented texts, annotated using the language TimeML [13]. TimeBank—is a free database of annotated English articles on different topics. It serves as a training sample to create neural networks and teach them to recognize temporal relations. However, the creation of such a corpus for the Russian language at this stage is not possible.

Another fairly small group of research and development is related to the methods of obtaining the temporal knowledge from the time series. Examples include [34]. Technologies of obtaining temporal knowledge from the time series, for example [31] are generally similar to that shown in [34]. The main advantage of this type of approach is their linguistic independence, which enables to use it in developments not related to the processing of NL-texts in Russian.

In [5] described a method of aggregation of temporal knowledge obtained from various sources related to the order of consideration of the proposed relationship between the temporal primitives (events, temporal pointer/marker), choice of most precise relationship with the level of confidence in the sources and recalculation of the levels of trust in sources on the basis of the decision. Thus, there is now a significant number of approaches to representation of temporal relations, but ways of obtaining temporal knowledge using the manual and/or automated methods, in the context of building a temporal KB, covered weak.

3 Features of Advanced Temporal Knowledge Representation Language Implemented in Task-Oriented Methodology

For representation of temporal knowledge through basic knowledge representation language (KRL) of AT-TECHNOLOGY workbench [16] was developed advanced KRL for dynamic IES (described in detail in [22, 28]), which allows to represent temporal knowledge, based on a modified Allen interval logic [1] and control in time logic [7], together with the basic knowledge, including knowledge containing uncertainty, imprecision and vagueness.

The main elements of the base KRL are objects and rules. The objects correspond with elements of PD and described as: Object $(IO, NameO, L)$, where IO—serial number of the object; $NameO$—the name of the object; L—the list of attributes, and the attribute of the object is: Attribute $(IA, NameA, Type)$, where IA—serial number of the attribute; $NameA$—the attribute name; $Type$—the class attribute, which has the form: type $(IT, NameT, U)$, where IT—Number attribute type; $NameT$—the name of the attribute type attribute; U—set of possible attribute values (a list of specific attribute values, or a range of values, which specifies the minimum and maximum values of the attribute, or membership function).

In generalized KRL event presented as object of PD with an attribute condition of the appearance. Type of this attribute is a logical expression, the value of which is a common logical expression that relates the attributes of other objects of PD, non-temporal primitives (this is a new type of element of the set U). The true value of the attribute “condition occurrence” at time T indicates that the event occurred at time T. In addition, the event also has an attribute of number of occurrences, which is an integer and describes the number of times an event observed in PD.

Temporal interval appears in the same way as an object with two key attributes —“start condition” and “end condition”. Both of these attributes are of type “logical expression”. The true value of the attribute “start condition” at time $T1$ indicates that the interval started at time $T1$, and the true value of the attribute “end condition” in time $T2$ indicates that the interval ended at time $T2$, i.e., the interpretation of this interval on the time-axis is the segment $[T1, T2]$, where $T1$ is always less than $T2$. Also, the interval has two attributes—“number of occurrences” (similar to events) and “duration” (integer describing the duration of the interval in the PD).

The rule in the base KRL represented as $(IR, Ins, Cons)$, where IR—serial number of the rules; *Ins* part of the rule which contains a list of pairs of the “attribute-value”, interconnected with logical relations conjunction and disjunction, *Cons* part of the rule that contains the list of attributes to assign values to them.

Consider the features of control in time logic, which requires the introduction of new types of KRL rules. On the one hand, such rules must provide rapid response to certain (usually emergent) events in PD (“rules-reaction”), on the other—need to be monitored in certain cycles (“recurrent rules”). “Rules-reaction” generally correspond to the modified Allen interval logic and represent the rules that contain the premise conditions of elementary formulas, which are subject to a single temporal object (event or interval). To represent the “recurrent rules” new attribute type presented, capable of taking one of two values: “Normal” and “periodic”. Parcels *Ins* of periodic rules carry an additional condition—the period of execution. Thus, the use of a modified Allen interval logic allows describing the temporal relationship between PD objects directly within the rules.

4 General Characteristics of the Combined Knowledge Acquisition Method and Perspectives of Creating a “Temporal” Variant

In general, the set-theoretic model of CKAM, which is described in detail in [16, 19, 22] and other papers, submitted in the form of:

$$M_{CKAM} = \langle N, S, F, K, Z \rangle \quad (1)$$

where N—unstructured description of PD (expert knowledge, documents); S—structured description of PD (field of knowledge); F—procedure of translating N to S; K—the procedure of conversion of the generated field of knowledge in a variety of formats of KRL.

Component N is a collection of background knowledge about the PD, as the constantly used as part of the basic tools of the AT-TECHNOLOGY workbench and received from various sources during the extraction of knowledge. I.E. : $N = \langle M_{mstp}, I, Ð¢ \rangle$, where $M_{mstp} = \langle M_{T1}, M_{T2}, M_{T3}, M_{T4}, M_{T5} \rangle$ a set of models for solving typical problems of diagnosis (M_{T1}), the design (M_{T2}), planning (M_{T3}), management (M_{T4}) and training (M_{T5}); $I = \langle I_{t1}, I_{t2}, I_{t3}, I_{t4}, I_{t5} \rangle$ specific knowledge learned from the experts through the use of model of solutions of typical problems (MSTP); $Ð¢ = \langle Q, D, W \rangle$ specific knowledge, acquired as a result of various methods of text processing, including NL-texts, where Q the knowledge obtained as a result of "understanding" of NL-texts describing how to solve the problem, needed to activate the appropriate interviewing script; $D = D_i$ knowledge gained by analyzing the combined protocols of interviewing experts for a few sessions, i = 1, …, n; W lexical knowledge (dictionary), obtained in the phase of analysis of system requirements of the user (ASTP) in the process of developing IES.

Component S is an intermediate representation of a set of structured knowledge —the field of knowledge, the main basic elements are the objects O_j and rules R_k, connecting these objects, i.e. $S = \langle O, R \rangle$, where $Ðž = O_j$, j = 1, …, m, $R = R_k$, k = l, …, c. Object $Ðž_j$ corresponds to one or more answers to the questions asked during the current session of interviewing.

The thematic structure of the dialogue [16–21] and the content of the questions to the expert focused on the fact that every response of expert interpreted as the name of the object, attribute name, the name of the attribute type, value or range of values of the attribute as well as the information included with the package, or the action of another element of the internal representation—rules Rk. The description of Object and Rule models has been given earlier.

Component F defines a set of procedures for internal low life cycle (LC) for forming fragments of the knowledge base from the field of knowledge, i.e.:

$$F = \langle F1, F2, F3, F4, F5, F6, F7, F8, F9, F10 \rangle \quad (2)$$

where $F1$—procedures to ensure the implementation of the initial stage of the life cycle of the knowledge base developing (selection and activation of dialogue script based on "understanding" of the input text); $F2$—service procedure for forming the current dictionary, including the collection of system analyst vocabulary in the analysis of system requirements phase and analysis of interview protocols; $F3$—procedures to ensure that the limits and characteristics imposed themselves as the current implementation CKAM and conditions of adaptation and adjustment to a specific PD (presence of static/dynamic area of expertise, specific methods of internal information representation, etc.); $F4$—procedures for identifying objects, attributes, attribute values; $F5$—procedures to identify the rules of connection between objects; $F6$—procedures for identifying specific differentiating features (if necessary) using the method of repertory grids; $F7$—procedures for identifying false knowledge; $F8$—procedures for knowledge extraction from the database (used at the stage of data mining); $F9$—procedures designed to generate graphical visualization and analysis protocols of sessions of the expert interviews (testing raw data); $F10$—logical test procedure (verification) for field of knowledge and knowledge base; optional $F11$—procedures of logical testing (verification) of KB, which are implemented after the transformation of the field of knowledge in a particular format of KRL dependent on PD.

K defines a set of component procedures to ensure consistent conversion of fragments of knowledge in the field relevant portions KB in terms of a KRL (user selectable). There are five main formats of KRL currently supported, i.e..: $K = \langle K1, K2, K3, K4, K5 \rangle$, where $K1$—the procedure of conversion into the KRL format of AT-TECHNOLOGY workbench, $K2$—the procedure of conversion into the KRL format of ECO; $K3$—the procedure of conversion into the KRL format of INTER-EXPERT (GURU); $K4$—the procedure of conversion into the KRL format of System Level 5. Object; $K5$—the procedure of conversion from field of knowledge to HT-format, view created hypertext (HT), call program modules from the HT-fragments. Z component describes the final result of CKAM in the form of consistent fragments of KB, i.e.: $Z = \langle Z1, Z2, Z3, Z4, Z5 \rangle$, where $Z1$—KB fragment in KRL format of AT-TECHNOLOGY workbench; $Z2$—KB fragment in KRL format of ECO; $Z3$—KB fragment in KRL format of system INTER-EXPERT (GURU); $Z4$—KB fragment in KRL format of system Level 5. Object; $Z5$—a fragment of KB as a hypertext.

Generalized model CKAM for the distributed knowledge acquisition represented in the form [19, 22, 24]

$$M = \langle N, S, F, K, Z \rangle \tag{3}$$

where $N = N_{locn}$, n = 1, …, mn—a set of unstructured definitions of PD; $N_{locn} = \langle IN, TN, SN, CN \rangle$, where IN—serial number of descriptions, TN—type of description, SN—the source of description, CN—in fact, the description itself; $S = S_m$, m = 1, …, m_m—a set of structured descriptions of PD; F—procedure of translating N to S, K—the procedure of conversion of the generated field of knowledge to a variety of KRL formats; Z fragments of KB in KRL formats.

Consequently, during the session of interviewing the expert the structuring of the information received as a field of knowledge carried out, an important function in the process of structuring obtained from expert information about PD providing a single internal representation and unification of the basic concepts and relations in PD, identified from a variety of sources of knowledge as a first step to formalization on a particular KRL. Therefore, taking into account the characteristics of the distributed knowledge acquisition the generalized model of field of knowledge can be represented in the form $S_m = \langle IS_m, TS_m, SS_m, O_m, R_m \rangle$, where IS_m—the serial number of a structured description of PD; TS_m—describe the type of structured description of PD; SS_m—source of a description; O_m = O_{mj}, j = 1, …, n—set of objects; R_m = R_{mk}, k = 1, …, p—a set of rules.

Thus, during the transition from a local variant of the acquisition of knowledge to the distributed, basic procedures of CKAM replenished the following procedures: obtaining descriptions from distributed sources; comparison of different types of fields of knowledge; clarification of definitions to identify inconsistencies; group knowledge extraction. Accordingly, the so-called temporal variant of the CKAM model will be linked to the modification and/or adding a new set of procedures and basic local procedures depending on the specific characteristics of the source of knowledge and the specifics of dynamic IES developed.

5 Conclusion

In general, base of CKAM technology is, on the one hand, the use of methods of interviewing experts (in local and distributed version), and on the other—the methods of automated knowledge acquisition from databases and NL-texts, thereby providing: the construction of the intermediate internal information description of the PD—field of knowledge; its verification on the presence of anomalies; elimination of these anomalies; aggregation of several fields of knowledge obtained from sources of various types; elimination of anomalies encountered after the aggregation; converting the acquired knowledge in the knowledge base on used KRL.

As noted above, CKAM originally developed for static PD, so now conducted research aims at its further development for use in dynamic PD for the acquisition of temporal knowledge in the format of modified Allen interval logic. From the perspective of building a fragments of field of knowledge the technological change is very small, because only the introduction of event and the temporal interval as well as adding to the premise of the rule of connections between these entities is necessary.

However, the main problems relate to the identification of these entities in the NL-texts received from the experts during the interviews as part of CKAM or distributed CKAM and use of sources of knowledge of different typology (databases, texts). Currently, these issues are under active research and experimental simulation. This work is supported by the Russian Foundation for Basic Research (project—15-01-04696).

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Collaboration of All-Purpose Static Solver, Temporal Reasoning and Simulation Modeling Tools in Dynamic Integrated Expert Systems

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Abstract The paper discusses scientific and technological problems of dynamic integrated expert systems development. Putting various inference tools together with simulation modeling tools gives a cumulative result in temporal knowledge processing.

1 Introduction

New opportunities of intelligent systems (in particular, dynamic intelligent systems) allow to increase efficiency of automation in known areas and to solve harder problems for which traditional methods and software aren't suited. The scope of scientific and technological problems interfering wide application of dynamic intelligent systems includes:

1. Difficulties of acquisition of knowledge that considers time from various sources such as experts, texts, databases, etc.
2. Difficulties of knowledge representations development for dynamic domains which can be characterized by evolving number of entities and external data updating in time.
3. The need for threading temporal reasoning for multiple asynchronous processes; high performance requirements for real-time applications; evolving data and even knowledge at runtime.

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4. Problems of modeling the dynamic system environment and its real-time evolution patterns.
5. High costs of special development tools for dynamic intelligent systems construction.
6. The need for special hardware for interacting with outside world (sensors, controllers, etc.).

Those problems explain the complexity of dynamic intelligent systems development and, in particular, dynamic integrated expert systems development. Still there is no universal approach addressing all these problems.

In late 90s at MEPhI there was developed a unique software tool for knowledge engineers—the AT-TECHNOLOGY workbench for applied integrated expert systems construction. It constitutes from an empty integrated expert system with scalable architecture and a wide range of implemented models and methods for solving both ill-formalized and formalized problems.

Analysis shows that approaches for acquisition, representation, and processing of temporal knowledge are least studied [1]. Ability to represent and use temporal dependences between occurring events allows to considerably reduce search space and affects the performance of dynamic integrated expert system. In modern tools (Gensym G2, RTworks, RTXPS, etc.) representations of time and temporal knowledge are rather simple and actually stay unused in the course of inference [2].

Thus, there is a need for models, methods, and software tools that deal with temporal reasoning in dynamic integrated expert systems. These models, methods, and software have to be integrated within uniform methodology and technology.

2 Models and Methods of Reasoning in Static Integration Expert Systems

The model of inference in the AT-TECHNOLOGY workbench considers both reliable and unreliable knowledge [3]. It takes into account such negative factors as uncertainty, inaccuracy, fuzziness, subdefiniteness of data and knowledge, and some others (together called NEG-factors). The key feature of this model is that all calculations with NEG-factors including fuzzification and defuzzification are carried out during inference lazily (as required).

On each inference loop partial evaluations of rule antecedents are performed. To maximize the use of evaluation results they are stored in working memory for the further loops. Truth-values of logical expressions lie within the set $[0;1] \cup \mathrm{NE}$ where NE stands for "not evaluated yet". NE corresponds to a case when a truth-value of an antecedent can't be calculated because working memory lacks some facts used in antecedent.

In matching phase there may be a need for transformations of NEG-factors for joint processing of rules containing unreliable information. A number of fuzzification methods are implemented for each data type and NEG-factor. Our experience in building integrated ES tells that fuzzy knowledge makes 1–2 % of knowledge base. Therefore using only fuzzy inference for such knowledge isn't adequate. So we do not totally fuzzify all data during inference but we fuzzify values only needed to calculate formulas with fuzzy values. At the end of inference we defuzzify all the values that became fuzzy. Membership functions are used to represent fuzzy values. It should be noted that during transformations in the course of inference some fuzzified values may become multimodal. In such situations our defuzzyfication method may give a set of accurate values corresponding to one multimodal membership function.

To accelerate conflict resolution we use a multicriteria algorithm of conflict resolution where calculations of rule ranks are done at matching phase. We consider specificity of rules, novelty of the facts, reliability of consequents. The conflict set is always ordered by rule ranks and persists through inference loops.

At backward chaining with lack of input data there are used some heuristics to ask for the needed parameter values:

1. First ask for parameters that are most frequently used in rules to give more chances to antecedents become fully evaluated.
2. First ask for parameters with larger value domains because they are possibly used in bigger number of competing hypotheses.
3. First ask for parameters that can be found in left-most conjunctions of LHS. Note that all conjunctions in rule antecedents are equally transformed from infix form like "a & b & c & d" where elements are ordered by importance to a prefix tree of the form "& (a, & (b, & (c, d)))".
4. First ask for parameters that can be found as mutually exclusive evidences in rules of the form "a_i & B → H_m" and "∼a_i & C → H_n", where H_m, H_n—hypotheses, B = b_1 & … & b_n, C = c_1 & … & c_n—conjuncts, a_i—weighed evidence. Getting one evidence excluded the other one and solver can reject one of the rules.

In all-purpose solver there are implemented control rules for unreliable knowledge processing. Processing of uncertainty, inaccuracy, subdefiniteness, and fuzziness separately can be fulfilled with the coefficients, attributes, intervals and membership functions assigned to values, statements, expressions and rules. But to process all that together we need to consider each pair of factors and design special matching techniques and methods of evaluating heterogeneous formulas. So at the end of inference any parameter value can bear in addition uncertainty or inaccuracy.

For interpretation of LHS and RHS of rules in all-purpose solver there were implemented arithmetic, logical, and comparison operations for various types of operands and NEG-factors. Basic arithmetic is extended to consider uncertainty and inaccuracy for the cases when at least one operand value is uncertain or inaccurate. If at least one operand is a membership function then we use fuzzification methods, fuzzy logic and Zadeh's extension principle. For linguistic variables which values are linguistic terms (strings) all-purpose solver replaces the terms by corresponding membership functions and also applies Zadeh's extension principle. Truth-values are all converted to [0;1] and may stay not evaluated as well.

3 Models and Methods of Temporal Reasoning in Dynamic Integrated Expert Systems

The offered model provides processing of knowledge containing temporal dependences together with basic knowledge in problem domain.

Temporal reasoning considers temporal and cause-effect relations between objects in the domain of interest. It also considers the possibility of changes both in data and knowledge. The model of inference generalizes the basic inference model described in [3] to address time. This model extends matching phase with interpreting event flow model, matching temporal and static fragments of rules; transformations and conversions of NEG-factors, and fuzzification. Rule firing in this model also considers NEG-factors.

In Fig. 1 activities that support temporal reasoning are shown in gray. Major challenges in integrating basic and temporal inference tools are: implementation of efficient reinterpreting event flow model; implementation of matching of global interpretation of event flow model built for all types of temporal expressions with local event flow models in production rules.

Thus, there are two goals of temporal reasoning: interprete current event flow model and generate the list of control actions to affect problem domain (or its model).

For representing problem domains in dynamics there were chosen Allen's logic [4] with some modifications and logic of control in time [5]. Allen's classical logic lacks some important features such as momentary events, quantitative characteristics of temporal primitives, etc. That complicates its application in dynamic integrated ES. So Allen's logic was modified to support these facilities based on ideas described in [6].

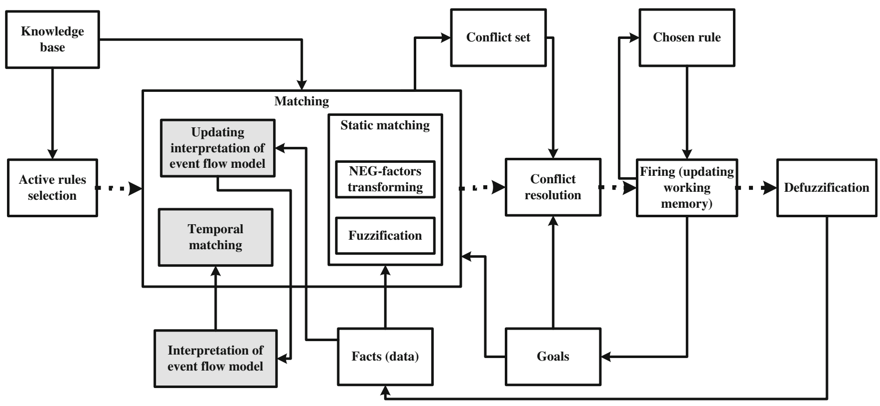

Fig. 1 Cycle of temporal reasoning on production rules

We shall provide here the description of Allen's logic formulas with modifications:

- X r Y expressions where X, Y—intervals and r—any Allen's connective;
- X r Y expressions where X, Y—events and r—one of {b, a, e};
- X r Y expressions where X—an event, Y—an interval, r—one of {b, a, s, d, f} where b (before), a (after), m (meets), o (overlaps), s (starts), d (during), e (is equal, synchronous with), f (finishes) are Allen's connectives;
- XH r N expressions where X—a variable, H—its attribute, r—a comparison operation, N—an integer;
- variables;
- simple formulas;
- ~f, (f & g), (f v g) where f and g are formulas.

Event flow model is specified by a set of temporal objects (events and intervals). Local event flow model in a rule is specified by Allen's logic formulas. Interpretation of event flow model is affected by the event occurrence times and by the intervals' start and end times. Application of Allen's logic with modifications assumes the concept of discrete time, i.e. changes in problem domain happen within cycles only.

Mechanisms of control in time allow to apply certain actions upcoming from changes in state of objects without introducing time explicitly [5, 7, 8]. Applying these mechanisms implies implementation of different methods of rule activation allowing to react to specific observed events and intervals.

For temporal knowledge representation in dynamic integrated ES there was extended basic knowledge representation language (KRL) of the AT-TECHNOLOGY workbench [9]. The KRL allows to represent basic problem domain knowledge including knowledge with uncertainty, inaccuracy and fuzziness. Generalized KRL in addition allows to represent temporal knowledge based on Allen's interval logic with modifications and logic of control in time. For this purpose there were introduced:

- new object types (event and interval),
- new types of attributes (logical expressions for origin conditions),
- changing in structure of LHS for the sake of local event flow model considerations,
- new types of rules (conventional, periodic, response).

The method of temporal knowledge processing allows to perform reasoning on knowledge containing temporal dependences by matching global event flow model interpretation with local event flow models. The main changes in basic inference model are incapsulated in matching phase: interpreting event flow model and processing temporal fragments of LHS of production rules.

Interpretation of event flow model puts events and intervals on time axis by identifying origins based on working memory data and reviewing history of their origins in the past. Special attention is given to cases of repeated origins and non-standard layout of events on time axis. For example, termination of an interval before its opening. Processing of temporal fragments of LHS of production rules uses the results of global event flow model interpretation. Local event flow models of active rules are checked to comply with this interpretation by means of Allen's logic with modifications and logic of control in time.

Temporal solver was developed and deeply integrated with the all-purpose solver within the AT-TECHNOLOGY workbench. That allows dynamic integrated ES successfully operate both in static and dynamic problem domains. During operation temporal solver performs two basic activities: interpreting event flow model and instantiating temporal fragments of LHS of production rules. Functional requirements to temporal reasoning tools stated in [2].

There were also developed some facilitation tools for collaborative functioning of components of expert systems and simulation modeling software within the new architecture of dynamic integrated ES. Some components also use working memory and dynamic blackboard to exchange data.

Recently there were developed several prototypes of dynamic integrated ES. Major advantages of models and methods used were speed of development and broader scope of applications.

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Some Aspects of Intellectual Tutoring Based on the Integrated Tutoring Expert Systems Usage

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Abstract The aim of this work is the analysis and synthesis of experience in the development and usage of tools for intellectual tutoring, functioning as part of AT-TECHNOLOGY workbench in the study process.

1 Introduction

Intellectual tutoring systems (ITS) occupy a significant place in a wide scope of intellectual systems issues. Interest to such systems arose greatly at the turn of the XX and XXI centuries. Educational sphere is a good "ground" for the application of artificial intelligence (AI) methods and tools, giving rise to a considerable number of approaches and system architecture solutions for intellectualization, individualization and web-orientation of processes of tutoring, learning and training.

Until now, there is an "information explosion" of publications both in Russia and abroad on the subject of the ITS. Without claiming to be exhaustive review of work in the field of ITS, we'll mention only some of papers [1–4, 6, 7, 9, 10, 21–24] and papers [5, 17, 19] reflecting the results of researches that were held in National Research Nuclear University MEPhI and other universities.

A great experience in the development and usage of tutoring integrated expert systems (IES) based on task-oriented methodology and powerful modern tools—AT-TECHNOLOGY workbench [13] has been accumulated in the "Intelligent Systems and Technologies" laboratory of "Cybernetics" department of National Research Nuclear University MEPhI. Educational IESs and web-IESs are fully functional new generation ITSs, that implement all the basic ITS's models (student model, tutoring model, problem domain model, ontology of courses and disciplines, etc.). As well, IESs allows solving wide scope of intellectual tutoring tasks, the main ones of which are [12, 15, 17]: individual planning of course/discipline studying technique; mining solution of educational problems; intellectual decision support.

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Process of knowledge level (declarative knowledge of a course/discipline) measuring and skills (procedural knowledge, which shows how this declarative knowledge could be applied in practice) detection is the basis for all mentioned above tasks. A number of methods for this purpose have been proposed.

To implement these processes there are a significant number of different methods, according to which the control tests and tasks have been developed.

For example, in tutoring IES network-orientated model of student is formed dynamically based on the analysis of answering questions from special web-tests. Generating of those tests is made with the genetic algorithms usage and method of estimation is based on generalized Roberts [13] estimation. Afterwards current student's knowledge model is compared with the course/discipline ontology. As a result of this compression one can determine so called "problem areas" in student's knowledge. There are other approaches to identify the level of student's knowledge, as described, in particular, in [3, 5, 6, 23]. However, with methodical, algorithmic and technological points of view the implementation of these processes is not particularly difficult.

Speaking of ITSs with ability of automatic detection of student's abilities to solve educational tasks of the particular course/discipline, it should be noted, that there are two main classes of them—highly formalized courses/disciplines (mathematics, physics, theoretical mechanics, etc.) and weakly formalized courses/disciplines which are usually representatives of the humanities, engineering, and specialized disciplines.

For the first class, problem of development computer based tools, which could reflect the methodology of tutoring and follow special requirements (which are usually developed personally by each tutor itself), is fairly well-developed and practically relying on ready-made solutions and standards.

Speaking of week-formalized courses, it is a much more complicated problem, as the process of detection of student's skills to solve educational tasks is related with modeling of a human reasoning. For such modeling completely different approaches are required. These approaches lay in a field of AI, particularly tools of classic expert systems (ES) and IESs.

For example, the teaching of special courses in the direction "Intelligent Systems and Technology" ("Database and Expert Systems (Introduction to intelligent systems)", "Expert systems", "Intelligent Information Systems", "Intelligent interactive systems", etc.) is connected with tutoring skills of students to solve such tasks as [14]: modeling the simplest situations of the problem domain based on frames and semantic networks, modeling strategies of forward/backward inference in the ES, constructing components of business sublanguage linguistic model and other.

Educational tasks listed above are based on in unformalized procedures. Big experience in the implementation of these procedures has been gained in traditional technologies of ES, particularly in knowledge engineering. according to [12, 15] "pros" and "cons" of using ES as it originally is for educational purposes, and it is shown that this concept includes much more than just a representation and processing of knowledge of the problem domain. Development from the basic mode "consultation with ES" to the mode "tutoring with control" allows: to monitor student's thoughts and mistakes effectively; to evaluate each step of solving the problem, and then, if necessary, to explain errors.

Similar ideas have been proposed in the early works of Petrushin [11] in the context of so-called expert-learning systems, but the rationale, development and experimental study of the concept was carried out only within the task-oriented methodology for the static, dynamic and PEC tutoring. The system for constructing tutoring IES (complex AT TECHNOLOGY) was created and tested in practice during the educational process in National Research Nuclear University MEPhI and other universities. It has special tools that implement "manual" methodic for solving week formalized problems.

The aim of this work is to analyze and get the best practices in developing and using tools of intelligent tutoring, functioning as part of AT TECHNOLOGY tool set [13, 16, 18] in the study process.

2 General Characteristics of the Tools of Intelligent Technology of Building Models of Students and Studding Process

In accordance with task-oriented methodology for constructing the IES [13], one of the most important components of a generalized model of a typical tutoring problem is the student's network model, which should be constructed and renovated dynamically by implementing control measures, provided by the curriculum of each course/discipline. There are special tools for building the student's model for these purposes. The tools are a part of the subsystem which supports construction of learning IES/web-IES and (subsystem) works in both versions (the basic and the web version) of a AT TECHNOLOGY tool set.

Let's consider a set of program components which are designed to detect student's skills to solve educational tasks in specific courses/subjects And which perform in a RunTime mode (i.e. interacting with student). Currently, on the basis of ontology "Intelligent Systems and Technologies" [20] the following four components were implemented and used in studying process [17]: (1) a component that detects student's skills to simulate the forward/backward inference, (2) a component that detects skills to build components of a linguistic model of business prose sublanguage, (3) a component that detects skills to simulate the simplest situations of the problem domain using frames, and (4) a component that detects skills to simulate the simplest situation in problem domain using semantic networks.

In the context of intellectual technologies in designing and developing IES [13, 18], these components are designed as informational and operational re-used components (RUC) that implement the standard design procedures (SDP) for constructing tutoring (training) IES (web). These set of SDP and RUC are the components of AT TECHNOLOGY intellectual programming environment [13] making a process of creating and operating a wide class of IES, including tutoring IES, be intelligent.

A Detailed description of the model of intellectual environment and its implementers is given in [13] as well as in several other papers [16, 18]. Here is presented a specification of operational and informational RUCs that copes with major issues of intellectual tutoring. A brief description of this RUCs is given below.

3 Individual Planning of the Course Studying Technique

Main operational RUCs for this task are the ontology of course/discipline building tools. Also there are about 10 information RUCs, associated with fragments of hypertext electronic manuals (HT-manuals) for specific courses/disciplines, and several information RUCs for building the generalized ontology "Intelligent systems and technologies."

In general, the current RUCs for the student model construction are the following:

- operational RUC "Student's knowledge level identifying component" (this RUC uses several informational RUCs to describe fragments of test problems for various fragments of the course/discipline ontology);
- 4 operating RUCs associated with student's skills level identifying (student's skills to model the forward/backward inference identifying component, student's skills to build components of linguistic model for business prose sublanguage identifying component, student's skills to model the simplest situation in a problem domain using frames identifying component and student's skills to model the simplest situation in a problem domain using semantic networks identifying component);
- 2 operating RUCs—"Psychological tests generator" and "Student's personal characteristics detection component". The process of psychological tests generation is carried out using informational RUCs containing fragments of copyright psychological tests aimed at the identification of the student's set of personal characteristics.

It should be noted that the component for displaying the current student's model, compared with ontology of course/discipline, is also designed as an operational RUC. It reveals the student's "problem points". That helps to construct the individual plan (strategy) of tutoring. The operational RUC "Tutoring plans (strategies) forming component" is used for the individual tutoring plan automatic generation, and special RUC "Tutoring impacts application managing component" is used for this plan implementation.

Each tutoring strategy includes specific sequence of tutoring impacts such as: reading of a hypertext manual; solution of several types of training tasks ("Building relationships between elements of the graphical representation," "Graphics organizing", "Entering a numeric value for the interval", "Graphics analysis", "Mapping and sequencing of the blocks", "Formation of the answer by selecting its components from the proposed list", "Marking the correction of the text", "Filling the gaps in the text", "Setting correspondences between blocks", "Entering the answer to the open question"); implementation of the tutoring impact "Training with IES"; explanation of the obtained results; tips; delimitation of made mistakes; solutions correctness control, etc.

Any tutoring strategy is characterized by a specific set of procedures and application of tutoring impacts, the content of which is determined by the degree of problem specialization, depending on the student's level of knowledge, skills and psychological portrait. Process of formation and implementation of all relevant tutoring impacts is supported by a special operational and informational RUCs.

4 Intelligent Analysis of Tutoring Problems Solutions

To identify the skills and abilities of student to solve tutoring unformalized problems from six courses/disciplines represented in a generalized ontology "Intelligent Systems and Technologies" [20] there were used simulations of student's reasoning for solving four types of tutoring tasks: modeling strategies of forward/backward inference, modeling of simple situations in problem domain using frames and semantic networks, building the components of the business prose sublanguage linguistic model.

Let's briefly comment operational RUCs that support the above tasks.

Operational RUC "Student's skills to model the forward/backward inference identifying component" and several information RUC's (fragments of knowledge bases) is designed to identify the learner's skills to simulate the forward/backward inference (courses "Introduction to Intelligent Systems", "Expert Systems", "Intelligent Information Systems"). Student walks through the following steps: KB fragment (production rules) creation; initial facts for direct inference input; creation of forward inference strategy model; facts and goals for backward inference input; creation of backward inference strategy model. To evaluate the student's skills, simple solver is used for performing standard inference and then comparing this inference (using special heuristics) with the student's solution.

Operational RUC "Student's skills to model the simplest situation in problem domain using frames identifying component" and several information RUCS (fragments of frames prototypes, represented in FRL language [14]) provide the declared functionality for the "Introduction to Intelligent Systems", "Expert Systems", "Intelligent Information Systems" courses. Student passes control tasks to create frames prototypes for problem domain defined by the tutor [14]. After that the student's level of skills is detected by comparison with the reference frames. A complete history of student's actions is saved and can be used to reproduce student's logic of reasoning and mistakes.

Operating RUC "Component of detection of skills to simulate the simplest situations in problem domains using semantic networks" and several informational RUCs (parts of semantic networks) provide the declared functionality within the following courses: "Introduction to Intelligent Systems", "Expert systems" and

"Intelligent Information Systems". A student is up to the control tasks by constructing a fragment of a semantic network for a given problem domain, and then the level of his skills is being assessed with regard to comparison with reference fragments of the semantic network and with the help of other expert techniques.

Operational RUC "Component of detection of skills to build components of a linguistic model of business prose sublanguage" and several information RUCs (dictionaries, fragments of business texts, etc.) provide declared functionality within the course "Intelligent interactive systems". Student is up to the control tasks by creating lexical, syntactic and semantic components of the linguistic model for a business prose text sublanguage [14], and then the level of his skills is being assessed with the help of special expert techniques.

5 Intelligent Decision Support System

It is important to note that in the development of tutoring impacts such as "Training with IES" for different formalized courses/disciplines, the most important task is to build a problem domain model (including knowledge-bases, containing certain types of NE-factors [13]). Another important task is the implementation of "consultation with IES" mode, which contains various scenarios of dialogues with the student. Within these dialogues considerable attention is given to explanations, tips and/or verification of the next stage of solving the problem, etc.

Here we could apply multiple operational RUCs from the AT TECHNOLOGY basic complex (communication subsystem, versatile AT-solver, an explanation subsystem, etc.), as the development of tutoring impact is the task of creating a complete IES. Informational RUCs are also used (knowledge bases fragments from previously created teaching operations "Training with IES", fragments of user dialogue scenarios in the "consultation with IES" mode, etc.), as well as operational RUC "Explanation component", which provides assistance at every stage of the solution of educational problems and particularly makes hints of the next stage, gives explanations of like "how" and "why" as well as it makes the visualization of inference.

6 Conclusions

Let us formulate some preliminary conclusions of experimental use of the tools described above in the learning process in National Research Nuclear University MEPhI.

- The main problem is the proper representation of the current student model (in this case, this is the information that characterizes student's skills and abilities to solve educational tasks). The information obtained remains incomplete and leads to inaccurate assessment of the actual student's skills;

- For solving study problems of formalized courses/disciplines it is not yet possible to build a good mistakes model (and its estimation procedure), and for some problem domains it is totally unclear how to build it;
- The main purpose of modeling the solution process of educational problems is not necessarily reaching the correct answer—it is important to learn how to solve these problems, i.e. it is about building skills, or modes of action, which correspond with the basics of the competence-based approach to tutoring.
- The availability of modern technology (for example, DHTML technologies) allows to achieve effective implementation of the basic components and their possible use in resource-limited timetable and sufficiently large contingent of students (about 1500 student model are handled).

Currently, experimental researches, re-engineering and further development of intellectual technology of tutoring IES construction's components are in progress.

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To the Question of Learnability of a Spiking Neuron with Spike-Timing-Dependent Plasticity in Case of Complex Input Signals

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Abstract Results of investigations of learnability of a spiking neuron in case of complex input signals which encode binary vectors are presented. The disadvantages of the supervised learning protocol with stimulating the neuron by current impulses in desired moments of time are analyzed.

Keywords Supervised learning · Spike-timing-dependent plasticity · Long-term synaptic plasticity · Neural networks · Computational neuroscience

1 Introduction

Currently there is a number of publications [1, 2] devoted to the various approaches to make spiking neural networks learn to respond with the desired output to an input. Among them learning by spike timing-dependent plasticity (STDP) looks like more biologically inspired and clear. Provided that the neuron can produce the desired output in response to the given input with some values of its adjustable parameters (i.e. synaptic weights), the question is when that desired parameters can be reached during learning, starting from random initial ones.

Legenstein et al. proved that STDP enables to realise supervised learning for any input-output transformation that the neuron could in principle implement in a stable manner. This fact was shown for Leaky Integrate-and-Fire neuron model, all-to-all spike pairing scheme in the STDP rule and simple forms of input signal, each synapse receiving Poisson trains of constant mean frequency. In [3] the same

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experiment was conducted with reduced symmetric spike pairing scheme, which is more biologically plausible according to [4].

In this study we investigate, following the protocol suggested in [5], the learnability of a spiking neuron in case of complex input signals. In Sect. 3.2 it is shown that synaptic weights, with which the neuron divides a set of binary vectors encoded by spike trains into two classes, can be reached during learning.

In this case the learning performance depends on the supervised learning implementation because of possible presence of undesired (unforced) spikes of neuron or absence of desired ones. To investigate the learning in idealized case without a spiking neuron at all, in Sect. 3.3 learning is performed without neuron, calculating weight change only on base of prepared couple of input and output signals.

In Sect. 3.4 the existence of short-term plasticity in the synapse model is shown to be not necessary for learning.

2 Materials and Methods

2.1 Neuron Model

In the Leaky Integrate-and-Fire neuron model the membrane potential V changes with time as following:

$$\frac{dV}{dt} = \frac{-\left(V(t) - V_{\text{resting}}\right)}{\tau_{\text{m}}} + \frac{I_{\text{syn}}(t)}{C_{\text{m}}} + \frac{I_{\text{ext}}}{C_{\text{m}}},$$
$$\text{when } V \geq V_{\text{th}}, V \rightarrow V_{\text{reset}}.$$

where V_{resting} was chosen to be 0 mV, $\tau_{\text{m}} = 30\,\text{ms}$ is the membrane potential relaxation time constant, $C_{\text{m}} = 30\,\text{pF}$ is the membrane capacitance, $I_{\text{ext}} = 13.5\,\text{pA}$ is constant background stimulation current, $V_{\text{reset}} = 14.2\,\text{mV}$, and $I_{\text{syn}}(t)$ is total incoming current through synapses. The refractory period was 3 ms for excitatory neurons and 6 ms for inhibitory ones.

As the synapse model we used postsynaptic current of exponentially decaying form along with the Maass-Markram short-term plasticity [6], taking all parameters as in [5].

2.2 Spike-Timing-Dependent Plasticity

STDP [7] is a biologically inspired long-term plasticity model, in which for each synapse a weight $0 \leq w \leq w_{\max}$, characterizing its strength, is given, and in the additive STDP form it changes according to the following rule [4]:

$$\Delta w = \begin{cases} -W_- \cdot e^{-\frac{t_{pre}-t_{post}}{\tau_-}} & \text{if } t_{pre} - t_{post} > 0; \\ W_+ \cdot e^{-\frac{t_{post}-t_{pre}}{\tau_+}} & \text{if } t_{pre} - t_{post} < 0. \end{cases} \quad (1)$$

with the auxiliary clause preventing the weight from falling below zero or exceeding the maximum value w_{max}:

$$\text{if } w + \Delta w > w_{max} \text{ or } w + \Delta w < 0, \text{then } \Delta w = 0.$$

Here t_{pre} is the presynaptic spike moment, t_{post} is the postsynaptic spike moment, weight depression amplitude $W_+ = 0,3$, and weight potentiation amplitude $W_- = \alpha \cdot W_+$, so that α controls how much the depression is stronger than the potentiation.

An important part of STDP rule is the scheme of pairing pre-and postsynaptic spikes when evaluating weight change. We used the reduced symmetric scheme, in which each presynaptic spike is paired with the closest preceding postsynaptic, each post- with the closest preceding pre-, and no more than once can a spike be accounted in pre-before-post pair and once in post-before-pre one.

2.3 The Learning Protocol

The following protocol suggested in [5] is to force the synaptic weights of a neuron to converge to the target weights:

1. *Obtaining the teacher signal*
   The neuron's weights are set equal to the target, STDP is disabled, and the neuron's response to the input trains is recorded as the desired output.
2. *Learning*
   The neuron's weights are set random (but about 4 times smaller than the target ones), STDP is turned on, and the same input trains are given to the neuron's incoming synapses. During this the neuron is stimulated by the teacher signal, obtained from the desired output train by replacing spikes with 0.2-ms-duration current impulses of 2 mA (which is at least three orders more than typical magnitude of synaptic current).

3 Experiments and Results

3.1 The Experiment Technique

The experiment configuration was chosen as in [5] in order to meet succession to the case of more simple input signals considered there. The single neuron had 90 excitatory and 10 inhibitory synapses. The neuron threshold was adjusted for each input signal to reach mean spiking rate of approximately 25 Hz. The maximum synaptic weights in the STDP rule (1) were chosen from the normal distribution with the mean of 54 and standard deviation of 10.8, values less than 21.6 and more than 86.4 being replaced by 21.6 and 86.4 correspondingly.

For the implementation of neuron and synapse models we used the NEST simulator [8].

As a measure for learning performance the deviation β between current and target weights was used:

$$\beta(t) = \frac{\sum_{i=1}^{90} \left| W^i(t) - W^i_{\text{target}} \right|}{\sum_{i=1}^{90} W^i_{\text{target}}}$$

So, the closer β is to 0, the more successful the learning is.

3.2 Learning Weights with Which the Neuron Classifies Binary Vectors

The aim of this section is to ensure whether a neuron can learn by the learning protocol under consideration such target synaptic weights that allow it to do the classification task. By doing the classification task we mean the neuron producing relatively high frequency in response to inputs represented by vectors from one class, and relatively low frequency in response to vectors from the other class. Binary vectors are encoded by spike trains, a vector component of 1 meaning high-frequency trains presented to the corresponding synapse or group of synapses, and a component of 0 being encoded by low mean frequency trains.

The output frequency of a neuron apparently must depend on how many spikes are given to the synapses having non-zero weights. Indeed, the output frequency depends almost monotonously from scalar product $(\vec{w}, \vec{S})$ of weights vector $\vec{w}$ by binary vector $\vec{S}$ describing input signal. This allows to obtain manually the weights with which the neuron classifies binary vectors. Six 100-dimensional binary vectors were generated, each having 50 components equal to 0 and 50 components equal to 1. Three vectors were randomly decided to belong to one class, and the other three —to the other class. Figure 1 shows that with the chosen target weights the difference between the neuron's frequencies in response to vectors from different classes is distinctly higher than difference in response to vectors from one class.

So, the weights with which the neuron classifies binary vectors were obtained, and such weights could emerge as the result of learning, as can be seen on Fig. 2. Since learning was less successful than in [9] (β never descended below 0.1, while in [9] it was less than 0.1), we tried changing the ratio α of weight decreasing

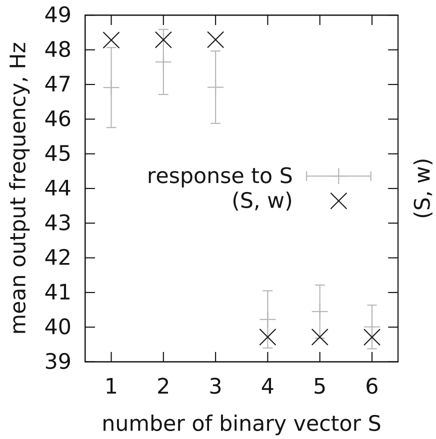

Fig. 1 For each of 6 binary vectors mean output frequency in response to the input described by that vector (a vector component of 1 corresponds to 30-Hz Poisson train, a component of 0–10 Hz), and averaged over 5 inputs described by the same vector, each presented for 100 s, is given (*gray bars*), along with the scalar product of that vector by the excitatory synaptic weights vector (*black crosses*)

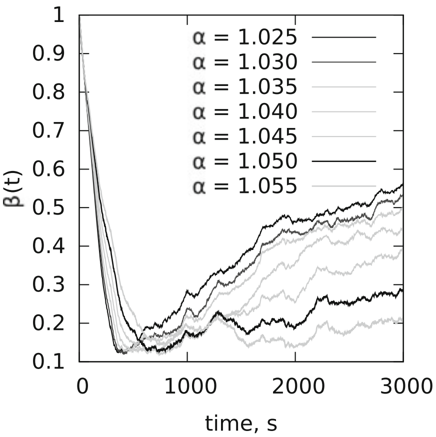

Fig. 2 $\beta(t)$ during training LIF neuron with different $\alpha = \frac{W_-}{W_+}$ in the STDP rule. 6 binary vectors presented one after another were used as input, a vector component of 1 coding a 100-s-long Poisson train with mean frequency of 30 Hz, a component of 0–10 Hz. Inhibitory synapses were always receiving 30 Hz trains

amplitude W_- to weight increasing amplitude W_+ in the STDP weight update rule (1), and the higher α is, the more successful the learning is.

3.3 Learning Without a Neuron, Based Only on Input and Output Signals and STDP Rule

The reason of rather poor weights convergence in the previous section is the emergence of unforced spikes, i.e. caused by the incoming synaptic currents instead of teacher impulses, and therefore differing from the desired output. To confirm it we introduced the learning protocol without neuron, in which spike pairing scheme is applied to the inputs and the desired output. Such a protocol provides the

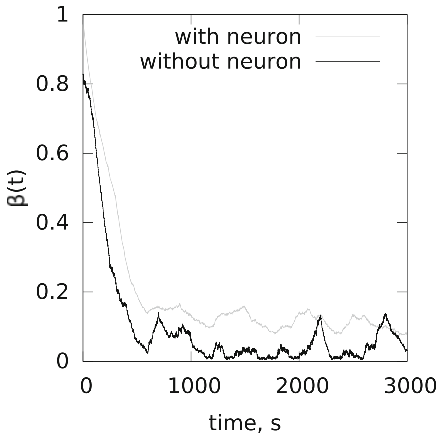

Fig. 3 $\beta(t)$ during learning: *gray* with LIF neuron, *black* without neuron, with the same desired output train obtained with LIF. Half of excitatory and all inhibitory synapses received Poisson trains with mean frequency of 30 Hz, and another half of excitatory synapses—10 Hz Poisson trains

idealised way of learning, with no difference between the postsynaptic train and the desired output. The "without neuron" curve on Fig. 3 shows that learning without a neuron is more successful than the one with neuron, copied from the previous section.

As a result, we conclude that differences in the learning performance of the protocols with and without the neuron are caused by the disadvantages of the protocol of presenting the teacher signal to the neuron in the form of current impulses, while, if the learning with some input and output trains was unsuccessful even without neuron, the reason would be that such input-output transformation cannot be learnt ever.

3.4 Learning Without Short-Term Plasticity

In [5] long-term plasticity model STDP was used along with Maass-Markram short-term plasticity model, but whether the existence of the latter is necessary for the weights convergence, was not stated clearly.

If one just removes the short-term plasticity variables $u(t)$ and $R(t)$ from the synaptic current equation, no learning is possible. The reason is that after long time of simulation (more than 20 s) u keeps fluctuating around about 1/2, while R—around about 1/8, so, removing u and R, the amplitude of synaptic current becomes about 16 times higher, which will inevitably cause undesired (see Sect. 3.3) spikes.

Nevertheless, if the synaptic current is multiplied by 0.04, which is roughly the typical mean value of $u \cdot R$ during simulation, the learning does take place (Fig. 4).

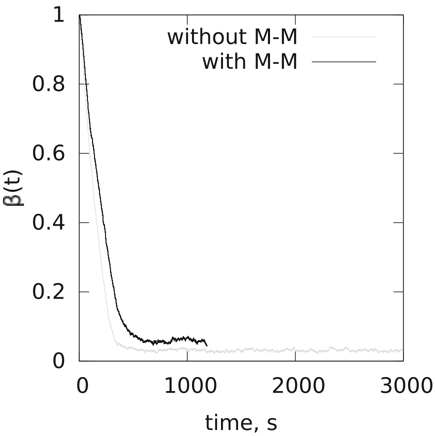

Fig. 4 $\beta(t)$ during training LIF neuron with and without Maass-Markram short-term plasticity. In the case without the synaptic current was being multiplied by 0.04. All synapses received Poisson trains with mean frequency of 20 Hz

4 Conclusion

Neuron learning can be performed using STDP not only with simple input signals, but with different complicated ones too. Slightly less accuracy in this case is caused by disadvantages of the protocol of stimulating neuron with current impulses during learning.

Changing the ratio of weight depression amplitude to weight potentiation amplitude can significantly affect the learning performance.

The existence of short-term plasticity is not necessary for learning.

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Causal Interactions Within the Default Mode Network as Revealed by Low-Frequency Brain Fluctuations and Information Transfer Entropy

Maksim Sharaev, Vadim Ushakov and Boris Velichkovsky

Abstract The Default Mode Network (DMN) is a brain system that mediates internal modes of cognitive activity, showing higher neural activation when one is at rest. The aim of the current work is to find a connectivity pattern between the four DMN key regions without any a priori assumptions on the underlying network architecture. For this purpose functional magnetic resonance imaging (fMRI) data from 30 healthy subjects (1000 time points from each one) was acquired and Transfer Entropy (TE) between fMRI time-series was calculated. The significant results at the group level were obtained by testing against the surrogate data. For initial 500, final 500 and total 1000 time points we found stable causal interactions

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between mPFC, PCC and LIPC. For some scanning intervals there are also connections from RIPC to mPFC and PCC. These results are in part conforming to earlier studies and models of effective connectivity within the DMN.

Keywords Effective connectivity · Default mode network · Resting-state fMRI · Transfer entropy

1 Introduction

Nowadays it is clearly understood that our brain is never at rest. During wakeful periods when we are trying not to do anything, global metabolism does not decrease in the brain, and some of its distinct areas are still active. These areas constitute networks of the resting state conditions or RSNs. Moreover, during overall inactivity and deliberate inattention to the external world, small but consistent increases in activity occur in a specific set of regions called the "default mode network" or DMN. It is a core part of a number of RSNs which were intensively investigated during a couple of decades. Transfer Entropy (TE) was first introduction by Schreiber [4] and has been recognized as a powerful tool to detect the transfer of information between joint processes. The most appealing features of TE are that it has a solid foundation in information theory and it naturally detects directional and dynamical information. Moreover, the formulation of TE does not assume any particular model as underlying the interaction between the considered processes, thus making it sensitive to all types of dynamical interactions [3].

2 Materials and Methods

2.1 Transfer Entropy

Consider a dynamic system consisting of X, Y and $\mathbf{Z}$—the stationary stochastic processes (X and Y are time-series of interest and Z contains all other processes), and X_n, Y_n and $\mathbf{Z}_n$ as the stochastic variables obtained by sampling the processes at the present time n. Let $X_n^- = [X_{n-1}, X_{n-2}, \ldots]$, $Y_n^- = [Y_{n-1}, Y_{n-2}, \ldots]$, $\mathbf{Z}_n^- = [Z_{n-1}, Z_{n-2}, \ldots]$ be the vector variables representing the whole past of the processes X, Y and $\mathbf{Z}$. Then, the multivariate transfer entropy from X to Y conditioned to $\mathbf{Z}$ is defined as:

$$TE_{X\to Y|\mathbf{Z}} = \sum p(Y_n, Y_n^-, X_n^-, \mathbf{Z}_n^-) \log \frac{p(Y_n|Y_n^-, X_n^-, \mathbf{Z}_n^-)}{p(Y_n|Y_n^-, \mathbf{Z}_n^-)} \tag{1}$$

where conditional probabilities can be interpreted as transition probabilities, quantifying to which extent the transition of the target system Y towards its present state is affected by the past states visited by the source system X [3]. From Eq. (1) it can be seen that TE assesses the new information provided by the past of the process X about the present of Y that is not contained in the past of Y or any other process included in **Z**.

2.2 Scanning Parameters

MRI data were acquired from 30 healthy subjects using a SIEMENS Magnetom Verio 3 Tesla. The T1-weighted sagittal three-dimensional magnetization-prepared rapid gradient echo sequence was acquired with the following imaging parameters: 176 slices, TR = 1900 ms, TE = 2.19 ms, slice thickness = 1 mm, flip angle = 9°, inversion time = 900 ms, and FOV = 250 × 218 mm^2. fMRI data were acquired with the following parameters: 30 slices, TR = 2000 ms, TE = 25 ms, slice thickness = 3 mm, flip angle = 90°, and FOV = 192 × 192 mm^2. Also the data which contain the options for reducing the spatial distortion of EPI images was received.

2.3 Preprocessing and TE Calculation

fMRI and anatomical data were pre-processed using SPM12 (available free at http://www.fil.ion.ucl.ac.uk/spm/software/spm12/) based on Matlab. Preprocessing included the following steps: Dicom import, adduction the center of anatomical and functional data to the anterior commissure, reduction of the spatial distortion using Field Map toolbox in SPM12 [2]. Next, slice-timing correction for fMRI data was performed (the correction of hemodynamical response in space and then in time to avoid pronounced motion artifacts) [5].

Functional connectivity in DMN is well studied, so for our DCM we took as regions of interest (nodes) most commonly reported four major parts of DMN: the medial prefrontal cortex mPFC [3, 54, −2], the posterior cingulate cortex PCC [0, −52, 26], left and right intraparietal cortex LIPC [−50, −63, 32] and RIPC [48, −69, 35] [1]. In square brackets there are corresponding MNI coordinates of centers of regions.

Multivariate Transfer Entropy was calculated using MuTE toolbox (available free at http://mutetoolbox.guru/downloads/) based on Matlab.

3 Results

For both real and surrogate data TE was calculated, the group mean (average across all 30 subjects) and median values are presented on Fig. 1.

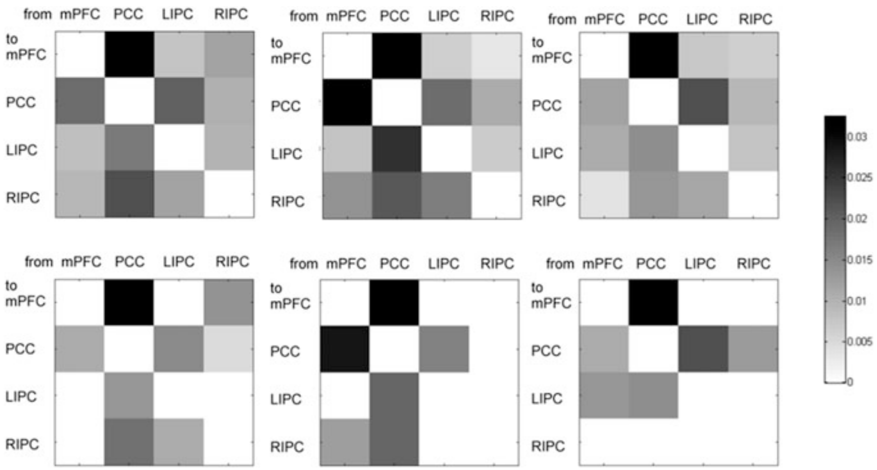

Fig. 1 Effective connectivity matrices. *Top* group mean TE values, *bottom* median TE values. From *left* to *right* matrices for total 1000 scans, initial 500 scans, final 500 scans

It can be seen that calculating the median value at the group level is a much more conservative approach then calculating the mean, taking into account that TE values cannot be negative. When calculating the median value, we got no false positives at all: for both 1000 and 500 scans, all values are equal to zero, i.e. we discovered no causal interactions between the random data. So, calculating the median is more appropriate (in terms of specificity) for group analysis then the group mean. From Fig. 1 (bottom row) we see rather strong and stable connections between mPFC and PCC (reciprocal) and between PCC and LIPC.

Next, for all scanning intervals (total, initial and final) two-sample T-test was performed between real and surrogate TE values at the group level. The null hypothesis is that the differences between real and surrogate TE values are normally distributed with zero mean. The T-test output (reject H_0—black square) is shown on Fig. 2 and can be used as a mask for TE group mean values: mean TE value is significant ($p < 0.05$) if the appropriate square is black.

From Fig. 2 we see the same stable connectivity pattern for all scanning intervals—between mPFC and PCC, PCC and LIPC (though for last 500 scans the connection from mPFC to PCC is not significant). For total and initial intervals there are also significant connections from PCC and LIPC to RIPC. For total interval, the connection between RIPC and PCC is significant. In general, from Figs. 1 and 2 we can see that connectivity patterns obtained by taking the group median and testing for significance against the surrogate data are much alike with minor differences. Only for the final interval t-test showed more conservative result than the group median. So, we can assume that for preliminary analysis of group TE values, the group median could be used.

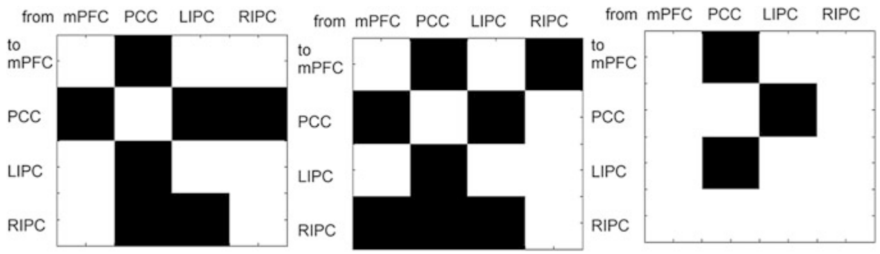

Fig. 2 The result of t-tests against the surrogate data. From *left* to *right* matrices for total 1000 scans, initial 500 scans, final 500 scans. *Black square* means null hypothesis is rejected ($p < 0.05$)

4 Discussion

In the current work we aimed at assessing causal interactions between the four key DMN regions: mPFC, PCC, LIPC and RIPC, not assuming any underlying model or hypothesis, how the observed data was generated. This approach has some advantages over model-based techniques (like DCM, Dynamic Causal Modeling). The main advantage is that we can perform exploratory analysis without having a priori assumptions on connectivity patterns. Transfer Entropy is a directed statistical measure, able to detect causality (effective connectivity) even if there is a wide distribution of interaction delays between the two fMRI signals [6]. TE is also able to detect frequently observed types of purely non-linear interactions between sources of activity. However, it has some irremovable disadvantages and limitations. First of all, TE values do not tell us anything about the nature and mechanisms of interaction. Model-based approaches, in contrast, provide parameters to researchers, which could be helpful to make and test assumptions on how the observed data was generated. These parameters could be synaptic plasticity, delays in conduction and many others. Next, if two systems are related by a deterministic map, no causality can be inferred. This would exclude systems exhibiting complete synchronization [6]. Also, self-connections cannot be assessed by Transfer Entropy. But despite all these limitations (resulting from Wiener definition of causality), TE could be very useful as an additional tool to model-based approaches, especially for preliminary analysis of experimental data.

From Figs. 1 and 2 we can see that for the final scanning interval we have lesser significant connections than for total interval and (in case of testing against the surrogate data) than for initial interval. As these three significant in the final interval connections totally overlap with significant connections for initial and total interval, we can assume that they are stable and reliable for all scanning intervals, while there could be not enough power to detect other connections in short intervals due to higher variability of data. This assumption could also be a result of comparing Figs. 1 and 2, for 1000 slices the result is practically the same, but for both initial and final 500 slices, results have more differences.

4.1 Funding

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Hierarchical Temporal Memory Implementation with Explicit States Extraction

Aleksey Skrynnik, Alexander Petrov and Aleksandr I. Panov

Abstract Hierarchical temporal memory is an online machine learning model that simulates some of the structural and algorithmic properties of neocortex. The new implementation of hierarchical temporal memory is proposed in the paper. The main distinction of the implementation is chain extraction module that complements the spatial and temporal polling modules of HTM. The new module simplifies cross-level regions connection implementation (e.g. feedback). An experiment is also described to illustrate how hierarchical temporal memory with explicit states extraction works.

1 Introduction and Related Works

Modern methods of artificial intelligence based on various approaches to modeling behavior of a person, require either to detail description of a priori knowledge of a problem to be solved by means of some formalism or require significant dataset for machine learning from which domain knowledge will automatically be extracted. In addition, the task of reusing a developed intellectual system in other tasks is difficult. Today intelligent systems are too much specialized, and a system which is capable to, for example, recognize a man, may be powerless in recognizing traffic signs or controlling a car motion.

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These problems are pushing researchers to deeper models of human behavior at all levels of cognition. Like so, new results in brain neurophysiology allowed Hawkins [1] to formulate a model of human neocortex, which has the following features: general cortical algorithm (algorithm for processing input information based on common principles that do not depend on the type of the information); hierarchy and invariance; sequences in time and predictions; online learning; different types of feedback; modeling attention.

This model, called hierarchical temporal memory (HTM), differs from many methods of data mining by its invariance to the nature of data to be processed, taking into account the time and existence of hierarchical relationships between features of the data. Unlike many machine learning methods which also have the capabilities listed above, hierarchical temporal memory does not require a separate phase of offline-training. The main purpose of HTM is to find causality in input data both in terms of time causality and hierarchical relationships between data elements.

The basic principle of the hierarchical temporal memory may be described as follows. The HTM assumes a tree-structured hierarchy of causation: top-level objects at the root of the tree (e.g. "square") determine the mid-level objects (e.g. "edges", "corners"), which ultimately determine the bottom-level observations at the leaves of the tree (e.g. "on pixel", "off pixel"). Bottom-up processing combines observed information to make an inference at the top-level: a line of "on pixels" implies a "line"; four "lines" and a "corner" imply a "square". Top-down processing communicates the context necessary to improve estimates: "there should be a line here, therefore this pixel should be on". The model assumes a temporal hierarchy, where top-level objects change slowly, and lower-level objects change more quickly: a moving square remains a square, but the pixels it moves across switch from "on" to "off" rapidly. This simplifies training: the lower-levels learn the fast patterns, leaving only the slower patterns for the higher-levels to learn.

There are various implementations of the model. One of the key model modules is a temporary pooler. In the first embodiment of hierarchical temporal memory this module is based on Markov chains clustering algorithm [2]. In [3] J. Hawkins and G. Dileep improve this temporal pooler implementation from the one hand describing a mathematical model of hierarchical temporary memory based on the belief propagation algorithm, and on the other hand presenting a comparison of HTM elements with known neurobiological structures, substantiating biological plausibility. In [3], Layer 4 estimates the node's current pattern from its childrens' estimates of their active sequences and Layer 2/3 estimates the probability of the node's active sequence from the current pattern (layer 4) and the memory of the last pattern. These is feed forward path. Layer 5 and Layer 6 implement feedback path. In our work we adhere the same concept, but propose a new algorithm, which translates the set of states of distal dendrites into the set of Markov chains.

The paper [4] provides detailed description (at pseudo code level) of HTM model programming—but it does not describe algorithms for multilevel network implementation. Similarly, in [5] a detailed description of one of the HTM regions implementation and parallel implementation for a multi-core processor are proposed. In [6, 7] authors describe their own implementations of temporary pooler, based respectively on the adaptive learning algorithm for sequence segmentation and belief propagation networks algorithm.

Thus the works known to us lack description of hierarchical temporal memory and the its training algorithm implementation, which on the one hand would be based on neural (biologically based) models [4], and on the other hand would describe the mechanism of interaction of several regions located on different network levels. Our solution of this problem is disclosed in the article.

2 HTM Model with Explicit States Extraction

2.1 The Basic HTM One-Level Elements

In our implementation the basic structural element of the HTM is a region. Regions form level hierarchy, where each region may be associated with the regions of the upper and lower levels by bi-directional communication.

The input for the network is a sequence of bit vectors that encode the input information. The output of the network is a next (predicted) state in the current or a new chain of states (Fig. 1).

The definition of the state of a region and the chain of states will be given in Sect. 2.2.

Consider the structure of a region. As in most implementations HTM region consists of spatial and temporal polling modules (on Figures—SP and TP, respectively). These modules are implemented in terms of arrays of columns that are composed of cells. In the case of SP all cells of specified columns are attached with one proximal dendrite to some elements of the input vector. In the case of TP various cells of each column may be connected to the segments of distal dendrite (Fig. 2).

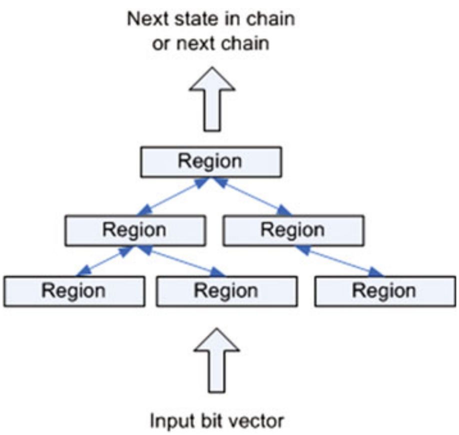

Fig. 1 The hierarchy of the regions

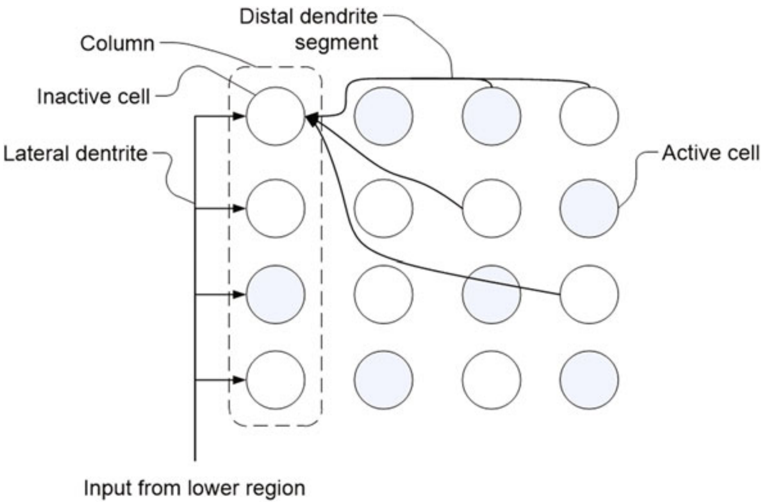

Fig. 2 Columns, cells and dendrites in region

The output of the SP is sparse distributed representation (SDR) of the input data. The benefits of using the sparse distributed representation and its key features are described in [8–10]. The output of the TP module is one step prediction about the sparse distributed representation, which can be returned as a feedback to the lower level region. Also TP module keeps a compressed representation of temporal patterns in the input data stream which were at the input. This representation is coded by segments of proximal dendrites, their properties and states of the cells.

A new element in the structure of the region is the CE module (chain extractor). This module implements chains extraction algorithm, which is described in Sect. 2.2 and allows moving from neurophysiologic representation based on the dendrites to the representation in terms of chains of states and transitions between them. CE module keeps the extracted chains and thus is able to transmit the next states predictions in the current or a new chain as a feedback for the lower regions (Fig. 3).

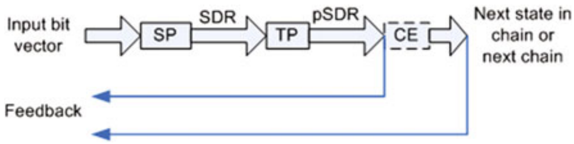

Fig. 3 Structure of region

2.2 Chains Extraction Algorithm

Consider chains extraction algorithm. Input data for the chains extracting algorithm are all cells stored in the TP module and dendrites between them. The output data are the states of the chain. We will consider all the dendrites.

1. For each dendrite a list of synapses with activation permanent should be found. Now consider those dendrites, which are activated by the activity from the cells of these synapses. Remember the cells to which the dendrites are connected.
2. Find dendrites, which are activated by a given set of cells, which dendrites are activated at one time. Remember the set of cells, which are connected to the dendrites.
3. Repeat the second step until not meet the previously stored state or there are not any dendrites with a non empty list of synapses with activating permanence.

Thus, this algorithm allows performing the transition from the compressed temporal patterns encoded in a variety of distal dendrites segments to their explicit representation in the form of chains of states. We give below the description of the experiment, which shows the operation of this algorithm on the example.

3 Experiment

To check the correctness of the implemented new version of HTM, we conducted the following experiment. There has been created and set up a network consisting of two layers, on each of which we placed a single region. The input to the network supplied encoded bit sequence of vectors that resembles the following: «a, a, b, b», where «a» and «b» are sequences themselves encoded with bit vectors (Fig. 4).

Bit vectors at the figure are presented as matrices for the sake of clarity.

Figure 5a shows the chain of states that were extracted by CE module after training the network first level region. As you can see, the first level region has correctly extracted and remembered two chains which are not related to each other. These chains encode patterns "a" and "b" respectively.

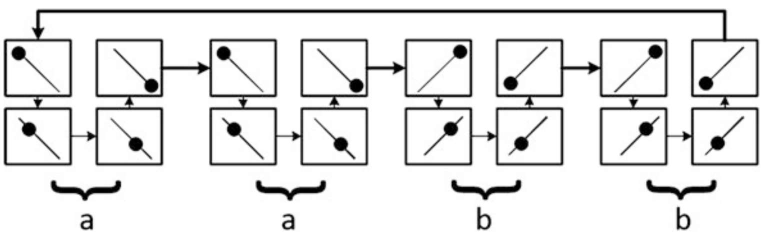

Fig. 4 Bit vectors «a» and «b». *Black dots* are coded by ones in bit vector

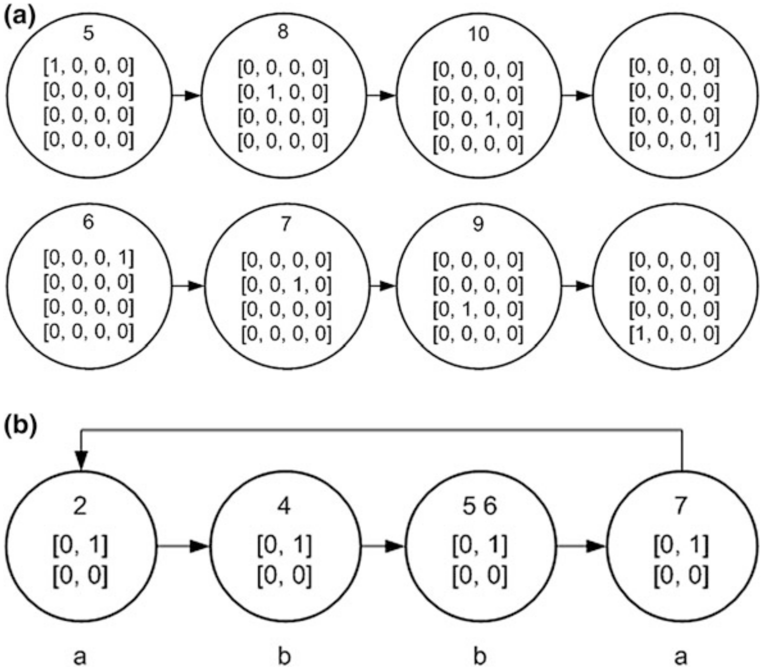

Fig. 5 Chains, extracted in the first level region

After the first level region training the learning process in the second level region was launched—the results of the CE module in the region of the second level are shown in Fig. 5b. As you can see the network correctly remembered the chain «a, a, b, b», which was used in this experiment. The experiment has demonstrated the main distinction if the presented in this paper HTM implementation—the CE module.

4 Conclusions

The new implementation of hierarchical temporal memory is proposed in the paper. The main distinction of the proposed implementation is chain extraction module, which complements the spatial and temporal polling modules of HTM. Our improvements of HTM allow implementing multilevel network with feedback. As a future work we plan to model visual attention process with new HTM implementation.

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Swarm MeLiF: Feature Selection with Filter Combination Found via Swarm Intelligence

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Abstract Combination of algorithms being called ensemble is a widely used machine learning technique. In this paper we propose a new method Swarm MeLiF which aims to find the best combination of basic filters and uses swarm optimization methods for this purpose. In this work we combine filters by combining the measures they use to evaluate feature importance. Thus, the problem of filter ensemble learning is reduced to finding a linear combination of these measures. We applied several swarm optimization methods and found that Particle Swarm Optimization shows the best results and outperforms the original MeLiF.

Keywords Swarm intelligence · Biologically-inspired meta-heuristics · Feature selection · Attribute selection · Ensemble learning

1 Introduction

Nowadays, biologically-inspired meta-heuristics (BIMH) are considered to be powerful tool for finding extremal points of non-analytical functions: minimize $f(x)$ defined on space X bounded with given constraints. In comparison with gradient-based methods, BIMHs make no assumption on $f(x)$ which is why they are claimed to be one of the basic black-box optimization techniques. Another reasons of these algorithms popularity is mimicking of the most successful natural biological processes [14].

Algorithms belonging to BIMH class are usually divided into [2]: evolutionary, ecological and swarm-based. Swarm-based algorithms mimic social behavior of

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species, such as ants or bees. Collective behavior of species allows to reach a tradeoff between exploration (performed by the swarm) and exploitation (performed by each individual). Swarm optimization algorithms are usually used when the variable space is topologically simple, such as $\mathbb{R}^n$, since their application usually requires support of operations such as finding a center of points, moving towards a point etc.

In this paper we try to apply swarm optimization algorithms to the problem of building a composition of feature selection algorithms. Feature selection is the important preprocessing step for many machine learning problems; it helps to remove redundant and noisy attributes with which objects are described. These algorithms are used for high-dimensional data preprocessing, such as DNA microarrays analysis. DNA microarrays represent measurements of simultaneous gene expression [10]. In this case the number of dimensions should be reduced carefully and the original features should not be changed. The main problem is that datasets for DNA microarrays usually contain many features and only a few objects, so feature selection is the best option for dimensionality reduction in that case [15].

The goal of this paper is to create an algorithm to learn ensemble of ranking filters measures via swarm intelligence.

2 Previous Work

2.1 Ranking Filters and Feature Importance Measures

Feature selection algorithms are preprocessing algorithms, thus, they receive a dataset as an input and return a dataset. Let $\mathcal{D}$ be the dataset space. Then a feature selection algorithm S is an automapping in $\mathcal{D}$. In contrast, classification algorithms which we will also use are mappings from $\mathcal{D}$ to a label space $\mathcal{Y}$.

As we previously said, ranking filter is a features selection algorithm that applies a feature importance measure to estimate each feature importance and then selects only those features that have high value of this measure. As we see, there two main questions which need to be answered: how to choose feature importance measure and how to define an exact strategy for selecting high-valued features (how many features to choose)? The formal definition of ranking filters provides answers for both questions. A ranking filter S is a pair (m, κ), where m is feature importance measure and κ is a cutting rule, which relates to a strategy of selecting the best features (and cutting off all the rest).

Ranking filters, say $S = (m, \kappa)$ work in the following way. Receiving a dataset $\mathrm{D} \in \mathcal{D}$ filter S first measures $m(f)$ for each feature f, then it ranks the features retrieving rank r, and finally, it applies the cutting rule.

The question of selecting a proper cutting rule is a problem itself, which we do not discuss in this paper. Thus we assume that the cutting rule is the same for all the filters we use in this paper. We are using standard deviation of feature measure m

for given feature list as a cutting rule. We will refer to it as κ. Under this assumption each ranking filter $S_i = (m_i, \kappa_i) = (m_i, \kappa)$. We will refer to such a filter as S_{m_i}.

The question of selection a proper feature importance measures is also a problem. A lot of different feature importance measure for classification exists. In this work we will use four feature importance measures. In order to describe them, we will first introduce a mathematical notation. Let k be the number of objects in the dataset, f be a feature, describing objects in this dataset, Y be the target vector, $f[i]$ be the value of the feature f for ith object.

We use the following feature importance measures: Spearman correlation coefficient (SC), symmetrical uncertainty (SU), value difference metric (VDM), and fit criterion (FC)—the same measures which were used in [11].

2.2 Feature Selection Ensemble Learning

As it was mentioned in the previous subsection, a lot of different feature importance measures exists. Assume we have a fixed set of different feature importance measures $M = \{m_1, \ldots, m_{|M|}\}$, where $m_i : F \to \mathbb{R}$. Nowadays, three common approaches are used to learn feature selection ensembles.

The first approach is in combining classifiers, that were learnt on different feature selection methods outputs [3]. De facto we do not combine nor feature selection algorithms, neither their results, instead we combine classifier results, which is classifier-dependent. Also we cannot simply change or optimize a cutting rule in this case. The second approach is in combining feature rankings [1]. This approach does not rely on feature importance measures, but solely to the resulting ranking. The last approach is in combining feature importance measures [6]. Let Comb be an $|M|$-dimensional functor. Then the method is: $\kappa(\mathrm{Comb}(m_1, \ldots, m_{|M|})(D))$. This approach does not lack generality and uses all the provided information. This is the approach we will use in this paper.

3 Swarm Optimization

3.1 Feature Selection as an Optimization Problem

First, we shall introduce feature selection as an optimization problem. Let D be described with a feature set $F = \{f_1, \ldots, f_{|F|}\}$, its target vector be Y, and Q be classification performance measure defined on the set 2^F of all the subsets of F, find such $F^* \in 2^F$ that

$$F^* = \underset{F' \subseteq F}{\operatorname{argmax}}\, Q(F').$$

In the assumption that we are given a set of ranking filters with the same cutting rule and under the feature importance measure combination approach the problem is reduced to the following one:

$$\theta^* = \underset{\theta \in \Theta}{\operatorname{argmax}}\, \kappa(\mathrm{Comb}(m_1, \ldots, m_{|M|}; \theta)(D)),$$

where Θ is a family of parameters for Comb.

In [11] Comb was chosen among linear functors, reducing the optimization problem to the following one: find a vector $A^* = \{\alpha_1, \ldots, \alpha_{|M|}\}$, such that

$$A^* = \underset{A' \in \mathbb{R}^{|M|}}{\operatorname{argmax}}\, Q\left(\kappa\left(\sum_{i=1}^{|M|} \alpha_i' m_i, F\right)\right) = \underset{A' \in \mathbb{R}^{|M|}}{\operatorname{argmax}}\, Q_A(A').$$

Now we can apply a swarm intelligence algorithm to solve this problem.

3.2 Swarm Optimization Methods

We use three different swarm optimization methods (SOMs). For each SOM we tried several different parameters configurations and set swarm generation limit to 10. Since all of them have 5 or 10 optimized instances, only 50 or 100 steps respectively is required for optimization algorithm to stop. Optimization area was set to $[-1; 1]^n$.

The first SOM is firefly algorithm [13]. In this method each starting point is a firefly, which has some coordinates and a fitness function value. On each step of the algorithm we estimate where this firefly should move, which depends on all other fireflies positions and fitness values. We took three different versions of this algorithm. In the first experiment, we took five starting optimization points. Then we added five random points to them, and tried to optimize this 10-firefly swarm. At last, we took five random points as the initial ones.

The second SOM is Glowworm swarm optimization [16]. In this method each glowworm has its own coordinates, fitness value, and dynamically changing luciferin and vision area. Also it has some limitations to maximum glowworms visible, probability $p = 0.5$ and $\gamma = 1$ as mentioned in [16]. In all experiments we took five good starting optimization points and five random points as described above. We conducted four experiments with different visibility radius v and maximum worms visible m such that: $v = 0.5, m = 3$; $v = 1, m = 3$; $v = 0.5, m = 5$; $v = 1, m = 5$.

The last method is the Particle Swarm Optimization method (PSO) [8]. In this algorithm several particles move around in the search space. Their movement is based on their local optimum and the global optimum known at the moment. We used several sets of parameters based on [8]: $\omega = 0.6, \varphi_P = 0.4, \varphi_G = 1.4$; $\omega = -0.2, \varphi_P = -0.3, \varphi_G = 2.3$; $\omega = -0.4, \varphi_P = -0.7, \varphi_G = 2.2$; $\omega = 0.4$, $\varphi_P = 2.5, \varphi_G = 1.3$; $\omega = 1.4, \varphi_P = 2.5, \varphi_G = 1.3$.

We should mention, as it was pointed out in our previous work [11], that for our problem points like $(1, 2, 3, 4)$ and $(2, 4, 6, 8)$ will show identical results, as the proportion between aggregated metrics will remain the same. It that article we used this property for our MeLiF method optimization. In the case of swarm algorithms, this feature could be used in a different way. In any swarm algorithm we somehow define optimization field boundaries. Assume that our boundaries are $[0; 1]^n$ where n is the search space dimensionality. Then some particle moves out from our boundaries, we should just rescale all the coordinates for all particles so that boundaries would become as they were before. The initial points of search are the following: $(1, 0, \ldots, 0)$, $(0, 1, \ldots, 0), \ldots, (0, 0, \ldots, 1)$, and $(1, 1, \ldots, 1)$. Also, for this methods, we tried to add five random points from $[0; 1]^n$, as the initial ones.

4 Experiment Setup

4.1 Experiments

The experiments were performed to compare new swarm-based algorithms with other ones, including our previous algorithm MeLiF (Measure Linear Form), and six methods, described in [11]. Four of them are filters with the feature measure described in a previous subsection. We will refer to them as "basic filters". The fifth algorithm is the well-known ReliefF algorithm which is one of the most effective algorithms for feature selection [12]. We use ReliefF with 1, 3 and 5 neighbors. And the last one is MeLiF method itself. We ran the algorithms at the same six DNA microarrays, described in Sect. 4.2. As the basic feature measures we used four measures, which are described in Sect. 2.1.

In our experiments, we also used widely-spread algorithm ReliefF [7], which usually has really high efficacy. In order to estimate results quality we used the AUC score, which is basically Area Under ROC-Curve. The experiment results are presented in the next section.

AUC is the well-known measure which is commonly used for estimating classifier performance. It estimates how good selected classifier performs on the given feature set. We selected support vector machine classifier (SVM) [4] as the classifier for the experiments.

4.2 Datasets

We used six DNA microarray datasets to compare the algorithms. Two of them were taken from Cancer Program Data Sets, from the Broad Institute.[1] We took the Breast cancer A dataset (1213 features, 98 instances) and the Leukemia dataset (15,061 features,

[1]http://www.broadinstitute.org/cgi-bin/cancer/datasets.cgi.

30 instances). The other four datasets were taken from the Bioinformatics Research Group of Universidad Pablo de Olavide Dataset Repository.[2] We use the Leukemia dataset (7129 features, 38 instances), the Lymphoma dataset (4026 features, 96 instances), the Central neural system tumors dataset (7129 features, 60 instances) and the Global cancer dataset (16,063 features, 144 instances).

Five of them are multi-labeled. We split each dataset with labels into c derivative binary datasets $d_1, \ldots, d_c$, such that every d_i was the one-versus-rest dataset for class i. Then we dropped some of these datasets, as some of them contained too few instances of one of the classes. For example, one of them is Lymphoma_NIL dataset with only 2 instances of NIL class over 96 total instances.

5 Results and Discussion

To compress the result representation, we aggregated the results of all the algorithms on each dataset for the derivative binary one-versus-rest dataset.

Since all the basic algorithms are outperformed by MeLiF, we will compare swarm MeLiF only with the original MeLiF. We excluded dataset "leubr", because all methods shown AUC equal to 1. The comparison of AUC scores for all the tested SOMs and MeLiF is presented in Table 1. The best AUC score for each dataset is emphasized in bold. All methods which outperform MeLiF are highlighted with grey. The complete table can be found online.[3]

Table 1 MeLiF in comparison with swarm algorithms

method	b_can	g_can	leu_upo	lymph	tumor
MeLiF	0.996	0.923	0.984	**0.996**	0.732
ff5	0.995	0.931	0.984	0.994	0.708
ff10	0.996	0.930	0.989	0.994	0.729
ff5r	0.993	0.901	0.994	0.990	0.717
gw(1.0; 0.5; 3)	0.995	0.928	0.989	0.995	0.716
gw(1.0; 1.0; 3)	0.995	0.924	**1.000**	0.993	0.748
gw(1.0; 0.5; 5)	0.995	0.930	0.978	0.987	0.712
gw(1.0; 1.0; 5)	0.995	0.933	0.984	0.978	0.711
pso(1.4; 2.5; 1.3)	0.997	0.930	0.984	0.993	0.779
pso(-0.2; -0.3; 2.3)	**0.999**	0.932	0.994	0.989	0.750
pso(-0.4; -0.7; 2.2)	0.998	**0.941**	**1.000**	0.993	0.756
pso(0.4; 2.5; 1.3)	0.997	0.940	0.994	**0.996**	**0.783**
pso(0.6; 0.4; 1.4)	0.997	0.930	0.984	0.993	0.776

[2] http://eps.upo.es/bigs/datasets.html.

[3] http://genome.ifmo.ru/files/papers_files/BICA2016/Swarm-AUC.pdf.

We can see that on the global cancer dataset almost all swarm methods outperform MeLiF. Moreover, PSO and Glowworm optimization with $v = 1, m = 3$ performs better then MeLiF or at least the same at almost all datasets.

6 Conclusion

In this paper we presented a new algorithm we called Swarm MeLiF which utilizes swarm optimization algorithms for finding the best linear combination of filter measures. This combination is used as a measure for a new filter with the same cutting rule. The results show that one of the proposed algorithm parametrization outperform MeLiF in all the datasets we used for test.

Many of the swarm optimization algorithms we have used reached the best results after several steps. This fact can be used to decrease algorithm performance time by early stopping based on optimization curve analysis. Another direction of further work is utilizing other hyperparameter optimization methods [5] for finding best parametrization of PSO algorithms we use in this work.

Other meta-heuristics can be applied under MeLiF framework, such as Local Unimodal Sampling (LUS) [9]. More generally, analysis of function landscape should be used to predict or synthesize the best search heuristic.

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Agent-Based Model of Interactions in the Community of Investors and Producers

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Abstract This paper presents an agent-based model of a transparent market economic system. The community of investors and producers is considered. The agents-messengers realize the information exchange in the community. The computer simulation demonstrates the natural behavior of the considered economic system.

Keywords Agent-based model · Competition · Agents-messengers · Transparent economy

1 Introduction

Agent-based mechanisms are widely used to solve multiple optimization tasks. For example, agents-messengers were used to solve the problem of optimizing a production hall's work and routing car traffic in a city [1, 2]. In the current paper, agents-messengers are utilized to optimize the functioning of the economic community of investors and producers.

Unlike other works on multi-agent economic models, this paper considers a simplified economic community that consists only of investors and producers. This helps to build and analyze the model with sufficient clarity.

In the community, there is competition, which can lead to the extinction of certain investors and/or producers; this is a characteristic feature of market

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economy. Though the economy is market-oriented, the economic characteristics of each subject of the community are open for the entire community and the interaction between investors and producers is clearly defined. Therefore, this economic system can be called "a transparent market economy".

2 Description of the Model

2.1 General Scheme of the Model

We consider a community of N investors and M producers; each of them has a certain capital K_{inv} and K_{pro}. The investors and producers operate in the transparent economy environment, i.e. they provide the information about their current capital and profit to the entire community. There are periods of operation of the community. For example, a period can be equal to one year. Further, T is a time period number.

At the beginning of each T period, a particular investor makes an investment into m producers. At the end of the period, every investor has to decide: how much capital should be invested into one or another producer in the next period. In order to take into account intentions of all investors, there is an iterative process, which is described in details below.

The i-th producer has its own initial capital C_{i0} before the period T. The producer obtains some additional capital from investors. The whole capital of the producer C_i is:

$$C_i = C_{i0} + \sum_{j=1}^{N} C_{ij}, \tag{1}$$

where C_{ij} is the capital invested into the i-th producer by the j-th investor at the beginning of the period T.

We believe that the dependence of the producer profit R_i on its current capital C_i is nonlinear: $R_i(C_i) = k_i\, F(C_i)$, the coefficient k_i characterizes the efficiency of the i-th producer, the function F is the same for all producers. In computer simulations, it was supposed that the function $F(x)$ has the form $F(x) = x^2/(x^2+a^2)$, where a is a positive parameter. The values k_i vary randomly at the end of each period.

At the end of the period T, the producer returns the invested capital to its investors. In addition, the producer pays off a part of its profit to the investors. The j-th investor receives the profit part that is proportional to the investment made into this producer:

$$R_{ij} = k_{pay} R_i(C_i) \frac{C_{ij}}{\sum_{l=1}^{N} C_{il}}, \tag{2}$$

where C_i is the current capital of the i-th producer, k_{pay} is the parameter defining the part of the profit that is transferred to investors, $0 < k_{pay} < 1$. The producer itself gets the remaining part of the profit:

$$R_i^* = (1 - k_{pay})R_i(C_i). \tag{3}$$

Each investor has the following agents-messengers: the searching agents and the intention agents; these agents are used for information exchange within the community.

2.2 *Description of the Iterative Process*

At the first iteration, the investor sends the searching agents to all producers in order to determine the current capital of each producer. At the first iteration, the investor does not take into account the intentions of other investors to invest some capitals into producers. The investors estimate the values A_{ij}, which characterize the profit expected from the i-th producer in the next period T. These values A_{ij} are:

$$A_{ij} = k_{dist}R_{ij} = k_{dist}k_{pay}k_iF(C'_{i0})\frac{C_{ij}}{\sum_{l=1}^{N} C_{il}}, \tag{4}$$

where C_{il} is the capital invested into the i-th producer by the l-th investor, C'_{i0} is the expected initial capital of the i-th producer at the beginning of the next period, $k_{dist} = k_+$ or k_- ($k_+ > k_-$). The positive parameters k_+, k_- indicate the level of the confidence of the investor for the considered producer; this level of confidence is k_+ and k_- for the tested and untested producers, respectively. At computer simulation, we set: $k_+ = 1$, $k_- = 0.5$.

Then the investor ranks all producers in accordance with the values A_{ij} and chooses m most profitable producers with the large values A_{ij}. After this, the j-th investor forms the intention to distribute its total capital $K_{inv\ j}$ among the chosen producers proportionally to the values A_{ij}. Namely, the j-th investor intends to invest the capital C_{ij} into the i-th producer:

$$C_{ij} = K_{inv\,j}\frac{A_{ij}}{\sum_{i=1}^{M} A_{ij}}. \tag{5}$$

At the second iteration, each investor uses the intention agents to inform the selected producers about these values C_{ij}. Using this data, the producers evaluate their new expected capitals C'_{i0} in accordance with the expression (1).

Then the investors again send searching agents to all producers and estimate the new capitals of producers, taking into account intentions of other investors. Profits of investors are evaluated by the expression (4), which already takes into account the intentions of all investors. The producers are ranked again and the investors estimate new planned values C_{ij} according to the expressions (4), (5). Once again, investors send intention agents to inform the producers about the planned capital investment values.

After sufficiently large number of similar iterations, the investors do final decision about the investments for the next period T. Final capital investments are equal to the values C_{ij} obtained by the investors at the last iteration.

At the end of each period T, the capitals of producers are reduced to take into account the amortization processes: $K_{pro}(T+1) = k_{amr}\, K_{pro}(T)$, where k_{amr} is the amortisation factor ($0 < k_{amr} \le 1$). The capitals of investors are reduced similarly (further, corresponding indicators are called inflation factors for convenience): $K_{inv}(T+1) = k_{inf}\, K_{inv}(T)$, where k_{inf} is the inflation factor ($0 < k_{inf} \le 1$).

3 Results of Computer Simulation

The described model was implemented into a computer program. The calculation parameters were as follows:

- the total number of periods of considered processes: $N_T = 100$,
- the number of iterations in each period: $k_{iter} = 20$,
- the maximal thresholds of capitals of investors or producers (exceeding these thresholds leads to the reduplication of the investor or producer): $Th_{max\_inv} = 1$, $Th_{max\_pro} = 1$,
- the minimal thresholds of capitals of investors or producers (if the capital falls below these thresholds, then the corresponding investor or producer dies): $Th_{min\_inv} = 0.01$, $Th_{min\_pro} = 0.01$,
- the maximal number of producers and investors: $N_{pro\_max} = 100$, $N_{inv\_max} = 100$,
- the initial number of producers and investors: $N_{pro\_initial} = 50$, $N_{inv\_initial} = 50$,
- the maximal number of producers m, in which the investor can invest its capital, usually $m = 100$,
- the part of the profit that is transferred to investors, usually $k_{pay} = 0.3$,
- the characteristic variation of the coefficients k_i: $\Delta k = 0.5$,
- the parameter of function $F(x)$, usually $a = 1$.

The initial capitals of investors and producers were uniformly distributed in the interval [0,1]. Since the calculation used random processes, averaging over 100 different calculations was performed in order to obtain reliable data.

The verification of the convergence of the iterative process. We obtained the dependence of the final total capital of all producers on the number of iterations (at $T = 100$). The results for the main value $a = 1$ [the parameter of the function $F(x)$] are given in Fig. 1.

It is evident that the iterative process converges within 10–20 iterations. Calculations were also done for the parameter $a = 10$, the convergence of the

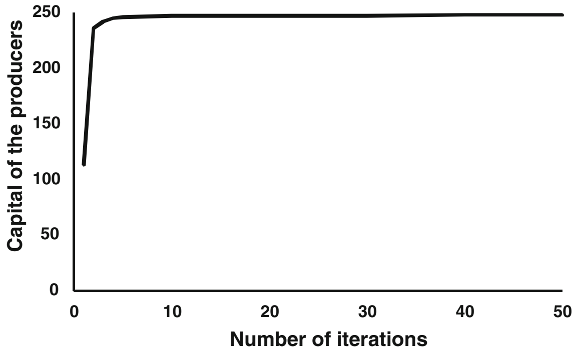

Fig. 1 Convergence of iterative process ($k_{amr} = 1$, $k_{inf} = 1$)

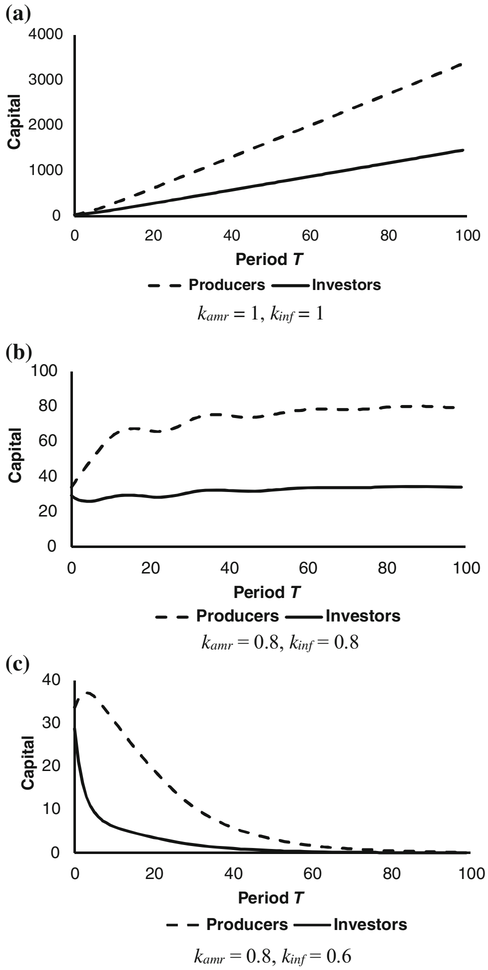

Fig. 2 Dynamics of capitals of investors and producers. **a** $k_{amr} = 1$, $k_{inf} = 1$, **b** $k_{amr} = 0.8$, $k_{inf} = 0.8$, **c** $k_{amr} = 0.8$, $k_{inf} = 0.6$

iterative process within 10–20 iterations was confirmed too. Taking this into account, the number of iterations was equal to 20 at our simulation.

The effect of amortization and inflation. If inflation and amortization are absent ($k_{amr} = 1$, $k_{inf} = 1$), the total capitals of investors and producers grow with time (Fig. 2a). In the case of moderate amortization and inflation ($k_{amr} = 0.8$, $k_{inf} = 0.8$), the total capitals of the investors and producers slightly increase (Fig. 2b). At large inflation ($k_{amr} = 0.8$, $k_{inf} = 0.6$), the total capitals of the investors and producers decrease (Fig. 2c); this means that the considered community dies.

The effectiveness of iterative evaluations. In order to show that investors are much more successful, when they make iterative evaluations of potential profits before making a decision, simulations were done for typical parameters in two cases: with the iterative process and without the iterative process. The simulation results demonstrate that the total capital of producers and investors is much higher in the model with the iterative process.

4 Conclusion

Thus, the agent-based model of transparent market economy has been designed and investigated. The model describes an effective interaction of investors and producers in the economic community. The agents-messengers ensure the information exchange within the community. The model can serve as a reference model for a wide variety of similar economic systems. Moreover, the presented model can be a reference standard for honest market economics.

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Patterns of Spiking Activity of Neuronal Networks in Vitro as Memory Traces

Ilya Sokolov, Asya Azieva and Mikhail Burtsev

Abstract Neuronal cultures in vitro plated on the multi-electrode arrays are very promising as an experimental model to study basic principles of learning that can later motivate development of new artificial cognitive architectures. But it is still an open question if patterns of spontaneous activity in neuronal cultures can be interpreted as memory traces and if these traces can be modified in a learning-like manner. We studied experimentally in vitro development of spontaneous bursting activity in neuronal cultures as well as how this activity changes after open or closed loop stimulation. Results demonstrate that bursting activity of neural networks in vitro self-organize into a few number of stereotypic patterns which remain stable over many days. External electrical stimulation increases a number of simultaneously present activity patterns with majority of bursts still classified as belonging to the dominant cluster.

1 Introduction

Today, artificial neural networks (ANN) represent one of the most common approaches to the implementation of biologically inspired cognitive architectures. Learning in artificial neural network is achieved by means of backpropagation

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algorithm. Unfortunately, it converges slowly thus prohibiting its possible use in applications that demand fast learning. On the other hand neural networks in the brain allow on the fly generation of solutions for complex problems thus ensuring survival of an organism. It is reasonable to learn from nature alternative forms of learning rules for neural networks that makes possible fast adaptation. There are experimental studies [1–5], demonstrating the ability of the network of primary dissociated cultures of neuronal cells on multielectrode arrays (MEA) to change own activity to learn switching off external stimulation. For the first time, such learning was demonstrated by Shahaf and Marom [6] and then successfully reproduced by other authors [7–10]. In this work we study the hypothesis that the neural network implements learning by detecting deviation from the homeostatic pattern of activity and reconfiguring to get rid of disturbing factor.

As a culture of neuronal cells matures in vitro a spontaneous electrophysiological activity emerges and can be recorded using the MEA. After a few days in vitro (DIV) individual spikes start to appear and in the course of the couple of weeks spontaneous activity of the network synchronizes into population bursts [11]. According to the proposed hypothesis spontaneous bursting activity should converge to a small number of stereotypic patterns representing a set of "memory traces" stored in the network. Hence, the application of cluster analysis to the spontaneous neuronal activity should results in the identification of a few or even single dominant pattern. Next, according to our hypothesis, stimulation disturbs a dominant pattern of activations and the network should change activity to turn off stimulation thus returning to back to the "normal" spontaneous pattern. So, the application of cluster analysis after stimulation or learning should identify the same dominant pattern(s) of activity as before.

2 Materials and Methods

Cortex and hippocampus cells were dissociated from the brains of the newborn mice and plated on a microelectrode array (MEA) consisting of 60 electrodes. To study the development of patterns spontaneous activity was recorded in 2 cultures once in a few days starting from 4 DIV. Learning experiment was performed with another culture on a 24th day in vitro.

Following protocol was used in a learning experiment.

1. Record spontaneous population activity for 1 h.
2. Apply single pulse stimulation with every electrode. Select an electrode that produces response with higher probability.
3. Open loop stimulation. Deliver 5 stimulation cycles via the electrode selected on the stage (2). One stimulation cycle consists of stimulation for 5 min followed by the rest period for 2 min. Stimulation consists of biphasic voltage pulses

spaced by few seconds. Delay between pulses is selected to be similar to the period of spontaneous population bursts.

4. Record spontaneous population activity for 1 h.
5. Closed loop stimulation. Perform 20 learning cycles. Every learning cycle is equivalent to the open loop stimulation cycle from stage (3) but with condition that allows breaking stimulation phase of the cycle. The condition for stimulation phase termination is the doubling of the probability of detecting a spike at a predetermined time interval on the electrode selected at the stage (3). If stimulation phase was terminated then the learning cycle is finished with the rest period for 2 min.
6. Record spontaneous population activity for 1 h.

Recorded signals were filtered and spikes were detected if amplitude exceeded 4 standard deviations. A burst event was defined as a train of high frequency spiking with duration of 0.1–3 s recorded on a single electrode. The burst is usually accompanied by a low frequency 1–5 Hz component. The detection of bursts was carried out by identifying of low frequency component in a predetermined window and detecting spikes around this component. An overlap of bursts on more than half of all active electrodes was detected as a population burst event. The beginning of the population burst event was set to the start of the first burst of the event.

Every population burst was represented by its activation pattern [1]. The dimension of the activation pattern vector V_k is equal to the number of active electrodes, i.e. electrodes in which there was at least one burst detected:

$$V_k = \left\{t_k(i) - t^k_{start}\right\}_{i=0}^{N} = (c_{k0}\ldots c_{kN}), \tag{1}$$

where $t_k(i)$ is a beginning of an activity on the i-th electrode, t^k_{start} is the start time of a population burst events. If for a given burst no activity was detected on the active electrode then the corresponding component of V_k takes an average value of the remaining components. Distance between activation patterns was calculated as a Pearson correlation. Weighted pair group method with averaging (WPGMA) [12] was used for the clustering population bursts.

To determine clusters it is necessary to find distances between adjacent vectors in an ordered sequence of vectors. Then to find a threshold value of clustering *th* based on the obtained distances. Nearby vectors form clusters if distance between them is less than the threshold. The threshold value *th* is defined as follows:

$$th = D\left(argmax\left(\frac{d^2D}{dn^2}\right) + 2\right), \tag{2}$$

where *argmax* is a function that returns the argument maximization, D is distances between adjacent vectors, n is number of clusters for current distance.

3 Results

Application of cluster analysis to the spontaneous population bursts along the neuronal network development for two cultures (Fig. 1) demonstrates that for the both cases more than 50 % of bursts belong to only one dominant cluster. Almost all of remaining population bursts falls into two equally sized clusters covering 40 % of bursts in total. This confirms previous findings [13, 14] that self-organization in the process of neuronal culture maturation leads to emergence of a limited number of dynamical modes with every represented by its own attractor.

Learning experiment was performed on the other neuronal culture. The electrode el62 was selected for the stimulation and the electrode el34 was selected to control termination of stimulation. The termination condition was set to detection of equal or more than 5 spikes in the 50–80 ms after the stimulus pulse.

The results of cluster analysis of the spontaneous population bursts of activity recorded on the stages 1, 4, 6 of the learning protocol are shown on the Fig. 2. Before the stimulation was performed (stage 1 of the learning protocol) population bursts are allocated to 2 large clusters #15 and #18). After the open-loop stimulation (stage 4 of the protocol) activity in clusters #15 and #18 decreases and clusters #2 and #4 become active. After the closed-loop stimulation (stage 6 of the protocol) activity in dominant clusters #15 and #18 remains on the intermediate level and the rest of activity had switched from clusters #2 and #4 to the cluster #3.

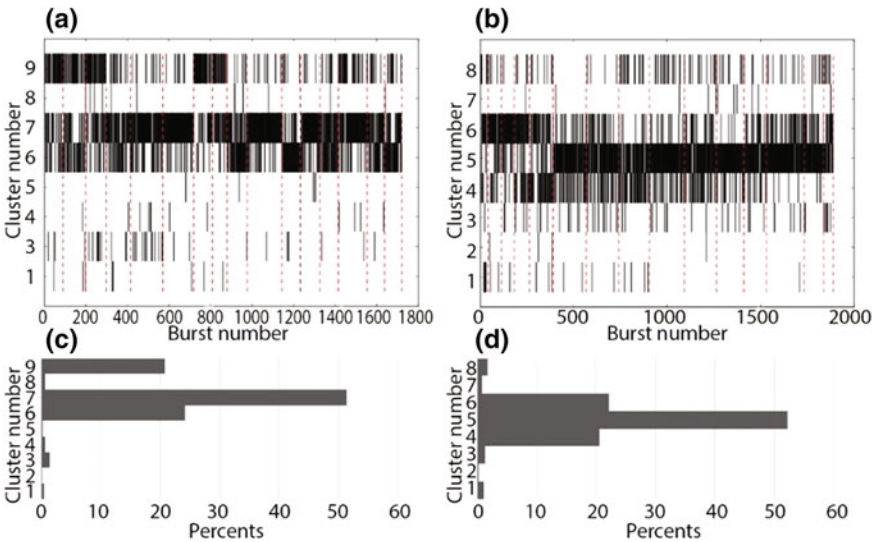

Fig. 1 Evolution of population bursts during development in vitro for the two neuronal cultures **a** 3035 and **b** 3040. Bursts are ordered in a sequence of appearance. The *red dotted lines* delimit the days of recording. The percentage of bursts in clusters for neuronal cultures **c** 3035 and **d** 3040

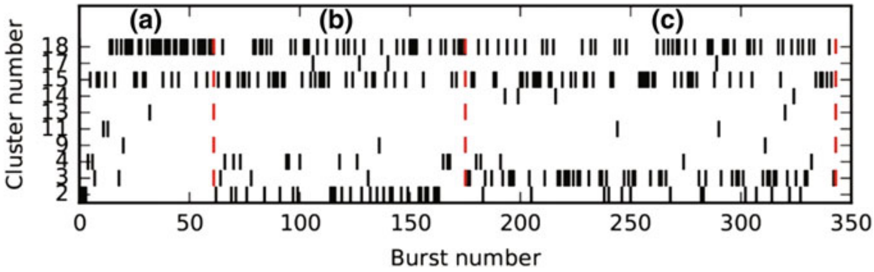

Fig. 2 Activity patterns switching after open and closed loop stimulation. **a** Before open-loop stimulation. **b** After open-loop stimulation. **c** After closed-loop stimulation

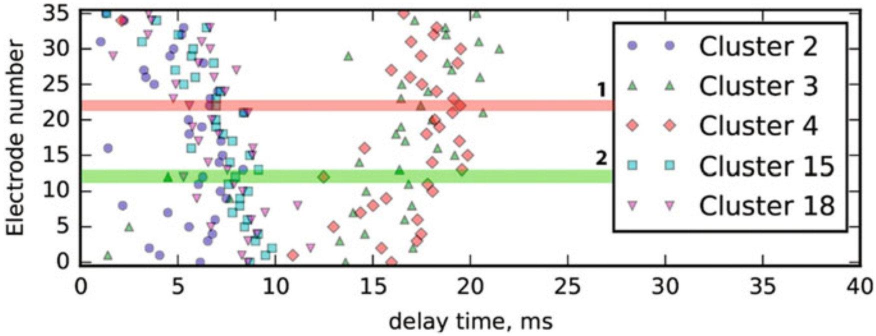

Fig. 3 The average feature vector for clusters containing at least 5 % of all the events shown in Fig. 2. The *red line* (*1*) shows which the culture were stimulated, the *green line* (*2*) shows the electrode through which the culture were learned

Dominant population bursts and activity that emerge after stimulation have significantly different patterns of activations (Fig. 3). Clusters #3 and #4 are similar to each other and diverge strongly from dominant clusters #15 and #18 that overlaps for a large extent. Cluster #2 combines features of the both groups. As all patterns were present before the stimulation and stimulation affected only their frequencies it can be suggested that learning is implemented mostly via switching between existing attractors of activity.

4 Conclusions

In our study we tested hypothesis that population bursts of activity in neural networks in vitro represents memory traces that can be potentially reconfigured by learning in the closing loop stimulation protocol.

The first prediction of this conjecture is that activity of a neural culture should self-organize into repeating patterns of activity representing memory traces. Our experiments confirm previous results [5, 13, 14] that dynamics of the network activity converges to a small number of attractors. Thus neurons in vitro are able to produce and sustain some sequence of activations that is prerequisite functionality for the memory storage.

The second prediction is related to the stability of the memory traces. Our experiments demonstrate that dominant activation patterns of the bursts are stable day by day in spite physical perturbations of the neuronal culture related to the medium change, removal from and placing in incubator, shaking and temporary cooling. Moreover, we studied how the change of activation patterns is affected by either open or closed loop stimulation. Our results show that dominant attractor of spontaneous activity is not destructed by any of the two types of stimulation. On the other hand diversity of patterns increased after the periods of stimulation. This allows assuming that learning in living neuronal networks is obtained by generation of variations of existing memory traces with consequent selection of the problem solving pattern. In protocol used in this study the "problem" was defined by external stimulation that can be switched off producing "solution".

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Ontology-Based Competency Management: Infrastructures for the Knowledge Intensive Learning Organization

Yury Telnov and Ivan Savichev

Abstract This paper devoted to a new method of competence management that introduced competence as a concept related to a resource-based view on an organization. It emphasizes the importance of this approach for the project-orientated and intensive learning organizations to address the problem of determining the trajectory of employees training and resource planning. Suggests the methods of modeling competencies, resources and knowledge using ontologies to automate the determination of the trajectory of training of staff and resource planning.

Keywords Competence management · Learning organization · Knowledge engineering · Ontologies

1 Introduction

Knowledge management is a big challenge especially in large organizations. Knowledge resides in many different forms: as explicit knowledge in documents and processes and as tacit knowledge in people and procedures and in many different forms between these two extremes. The vision of the Semantic Web is to offer more intelligent services by facilitating machine understanding of web content. Ontologies are an important building block in Semantic Web. An ontology describes the concepts, their relationships and properties within their domain, and it can be utilized both to offer automatic inferring and interoperability between applications. This is an appropriate vision for knowledge management, too. This paper describes how Semantic Web ontologies can be utilized in a research organization to create a common language to describe its knowledge. The same ontology can be utilized to manage projects, people, documents and products.

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With a common ontology, information that is spread out in many different applications and documents can be viewable in a way that is easy to understand and navigate. The ontology makes it possible to search both knowledge content and experts who are linked to different topics, thereby bridging the gap between the tacit and explicit knowledge Document Header. One of the main ways to increase the efficiency of the organization with the use of ontologies and knowledge management methodologies models is a project competence management. Competence is dealing with the ability of the staff to act in a responsible and adequate way while combining vital skills, experience and creative knowledge in order to meet emerging challenges. Competencies are described as a set of requirements to knowledge, skills and quality of a worker to reflect his/her functions, placement or a role in the project. If professional skills, knowledge and personal qualities of a specialist coincide with the competence requirement of a certain occupation the performance under favorable conditions will be effective. The results of competency assessment can help in unlocking full potential of the organization, in building proper and adequate trajectories of individual and corporate learning and maintain highly closed resource gap to provide a sustainable growth of project management result.

2 An Ontology Engineering Approach to Competence Management

The term “ontology” has its origins in metaphysics and philosophical sciences. In its most general meaning, an ontology is used to explain the nature of the reality. There are at least a dozen of definitions of ontologies in the computer science literature, but the most widely cited is that provided by Gruber [1]. For Gruber an ontology is a high level formal specification of knowledge domain: it is a formal and explicit specification of a shared conceptualization. An ontology is a basic structure around which a knowledge base can be built [2]. However, ontology itself is not a formal programmatic representation. Our approach includes a hierarchy (taxonomy) of concepts based on graph theory and semantic networks in order to represent more complex relationships and domain constraints. At this stage, the control vocabulary should be extracted and defined in order to create the first conceptual model. Other domain ontologies can then be reused and incorporated as appropriate (Fig. 1).

The generic model to represent competencies includes the following aspects:

- A taxonomy for primitive (general, technical, and behavioral) competencies.
- A taxonomy for application area.
- Entity (individual, group or organization) profile representation.
- Project management model and related competencies.

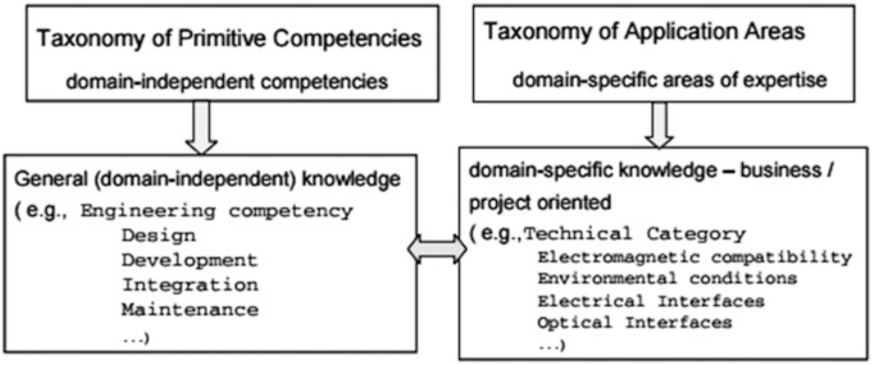

Fig. 1 Example of an organizational competency [4]

Examples of primitive (or generic) competencies might be cognitive (understanding, reasoning, and creativity) and technical (modelling and analysis) competencies. Examples of application areas are domains (or organizations) that are reasonably well defined, such as a software development company, a university, an insurance company or a pharmaceutical company. Organizational competencies (see Fig. 2) refer to capabilities, skills, proficiencies, expertise and experience achieved during daily work. There are two types of competencies: technical and

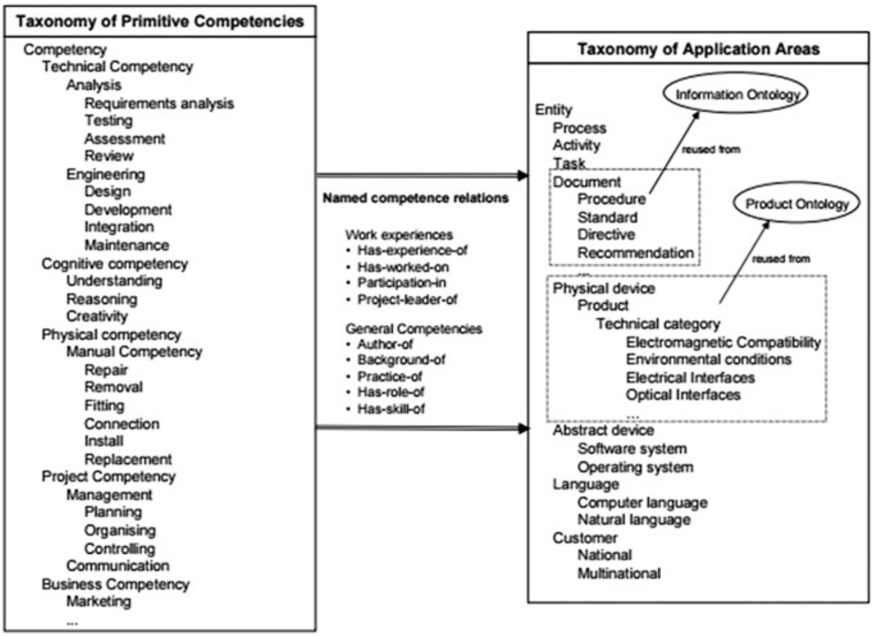

Fig. 2 Example of a competence taxonomy [4]

non-technical. The initial focus for this work was a software development company and the related technical and non-technical competencies. These competencies are often referred as professional skills. Nevertheless, the non-technical competencies (or primitive competencies) should be considered as part of the proposed competence model.

3 Using Competencies Model by Organization Needs

One of the objectives is to measure the competencies management competencies. Competence—a latent variable that can not be directly observed. For these concepts necessarily carrying out the process of operationalization.

Operationalization—is the process of identifying concepts with a set of specific empirical actions, operations, maintenance synonymous concepts [1]. Operationalizing allows you to split, to clarify and refine the core concept, to put it under a set of conceptual and empirical indicators [2]. In other words, in order to more accurately understand what competence is necessary to determine which concepts are close, and how they are related to the concept of competence in the context of our proposed model. This will generate diagnostic tools competences.

Let us examine the relationship of the following concepts with the notion of competence: action, skill, talent, ability and knowledge.

Considered below are the concepts conceptual indicators of the general concept of—competence. They offer the potential to develop even more specific concepts that can become true indicators for the definition of competence.

Act. In terms of the proposed model, as we have already identified, action is an integral part of competence. Competence does not exist until the subject does not take action to achieve this goal. On the other hand under the action we understand something objective, while competence refers to a subject. Competence—is a pure concept, while the action admits errors, violations, which is why for a little understanding to understand the essence of the action, which carries a subject, a broader concept—the competence.

Qualification. Immediately, we note that the qualification is not synonymous with competence. The bottom line is that the qualification is inseparably linked to the institution in which the action takes place. A person can be trained, but that does not mean that it is competent in the activity. Qualifications linked to the formal signs—diplomas, certificates, certificates that are recognized by the Institute. Man is qualified within the institution, but it is competent or not, determines only the result of its activities.

In terms of models, qualification is at the bottom of the cup of hours, but at the same time, we note that there is an integral part of competence. Here, as an example, self-taught artist. It may be unskilled artist from the point of view of society (where the Company acts as an institution), but if it works like the people, that is, the result is achieved, it will surely be called competent. Although there is another problem—the definition of criteria of achievement, since it depends on who is considered competent. These criteria, as we have already noted, it establishes institute and qualification is a projection of these criteria. That is why social skills are often considered to be the primary sign of competence.

Qualifications often only shows that the person has the minimum requirements to be deemed competent. This fact must be taken into account in the application of real competence-based approach in practice. Ideally qualified to be synonymous with competence. A qualified person must always be competent within their field of activity.

Endowments. Like other personality characteristics, giftedness refers to those characteristics that define the solution of the problem. Giftedness is part of the person, and determine its behavior, but it is cut off from the bottom of the bowl hours. Giftedness can be a person, but not to be used to achieve the task, the person may not even be aware of the presence of his talent, which means that it is no longer a part of competence.

Often the presence of genius, as the characteristics of the individual determines the best execution of the personality of this type of activity. There are general and special talent. So, overall mental talent manifested in the mastery of all the activities, for which successful implementation requires certain mental qualities. Special talent is associated with a variety of activities in which it is revealed most (mathematical genius, tech, music, fine art, poetry, etc.). Similarly, we can say that competence may be general or specific. You could say that talent pervades competence on all sides, no matter what jurisdiction we are investigating, but it does not define it completely.

Note that talent is often associated with the most appropriate and effective implementation. Availability of talent promotes best execution.

Knowledge and skills. Knowledge and skills do not coincide fully with the terms of reference. Knowledge is an intrinsic characteristic of the individual, and skills increasingly determine the nature of the action performed. We can say that knowledge is a prerequisite skills personality and skills is determined largely effective action to achieve results [3].

The K-Engine aims to quantify knowledge in a process called Skill Quantification. The skill quantification process applies rules to skill metrics and evidence in order to quantify the knowledge represented by a single skill. The goal here is to produce a suitable uniform metric for quantifying skills. Knowledge quantification aims to answer the following questions:

- How much does someone knowledgeable about a specific area of knowledge?
- How sure are we that they effectively know this?
- How do we measure and assess that knowledge?
  The answers lie in evidence in the same way as a driver's license is an evidence of qualification to drive a certain category of vehicle. The use of quantified evidence brings a certain level of reliability to the evaluation of expertise, although different forms of evidence have different degrees of reliability and different types of metrics are used to express this expertise. The quantification of knowledge is described using two different values:

- Quantification value (how much is known)
- Reliability value (how sure are we about it). There are two types of rules, quantification rules and quality assessment rules, both are expressed as mathematical expressions in which the metrics and evidence can be manipulated numerically. A quantification rule seeks to aggregate metrics into a single numerical value, a quantification rule may use all of the available metrics and evidence or focus on particular types of either one; different weights or modifiers may also be applied.

Thus, the quality rating value does not modify the quantification value, but complements it. Authors suggest to use Euclid's distance of the average level of the person's competencies from the required level for the project for finding the assessment of the competencies of the personnel (Δ i) in the frame of separate projects:

$$\Delta i = \sqrt{\sum_{j} Y_{ij}(K_{ij} - C_j)^2} \rightarrow \min \tag{1}$$

where Δ i—Euclid's distance
Y_{ij} = 1, if a j-competence is being used in an i-project; 0 if not
K_{ij}—a required level of j-competence for i-project
C_j—an average level of j-competence of company's personal.

Consequently Euclid's distance is out of the limits of the required deviation if the learning of the personnel or the recruitment of different categories of workers are needed:

$$\sum \Delta i \leq \delta \tag{2}$$

The inputs to the process of competency gap analysis can be considered as a logical formula instead of a collection of required competency levels and intensity [3–5]. This enables the specification of alternatives in competency acquisition. For example, strategic directions inside the company may require new competencies in Product X or Product Y to face forthcoming technological challenges (Fig. 3).

Needs are described in terms of competency descriptions, so that for a given need, a triple (CD i, level i, INT i) is defined with the following three components: – The Competency Description (CD) itself, as an expression of the required competency. – The level desired for that competency, expressed as an overall aggregate level, which will be mapped to the levels of individuals inside the organization. – The intensity required (INT), that is, the "volume" or "quantity" of the competency. This is an estimation of the required part of the workforce that is desired to have the competency. Components of competence together with the prescribed level of their formation must be specified in the model of project's competence profile in the form of ontology model.

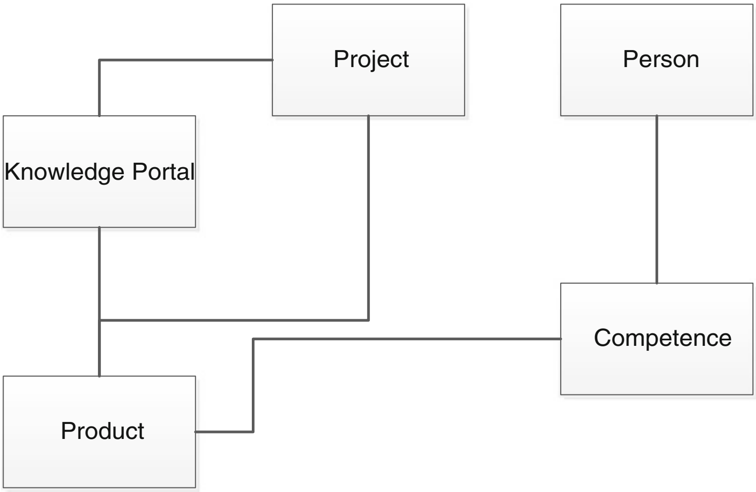

Fig. 3 Connections between the existing knowledge sources

4 Conclusion

Ontologies provide a shared and common domain understanding in order to enable the communication between people and application systems. To develop effective knowledge management systems, it is becoming essential the definition of shared and common domain structures in the form of organizational memories or shared information spaces. In this context, ontologies are emerging as an essential asset in knowledge representation, to describe both the structure and the behavior of unstructured and semi-structured information and can be used when assessing the level of competence of the personnel with respect to ongoing projects.

Acknowledgments The funding for this research was provided by the Russian Science Foundation, Grant RSF No. 14-18-00519.

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The Approach to Modeling of Synchronized Bursting in Neuronal Culture Using a Mathematical Model of a Neuron with Autoregulation Mechanism

Dmitry Volkov and Olga Mishulina

Abstract The paper presents mathematical model of spike activity of a neuronal culture which exhibits bursting behavior—synchronized spontaneous packs of population activity. Neuron in the developed neural network model is a modification of Leaky Integrate-and-Fire neuron. The neuron model acquires a new quality due to the introduction of two new neuron state variables—“resource” and “strength”. The new learning mechanism for synaptic weights is proposed. It assumes dependence of weight corrections from the intensity of spike activity of presynaptic neurons for a previous time interval. The model experiment shows the ability of the neural network based on the proposed model of neurons, to produce bursting activity. Setting of neuron model parameters makes it possible to obtain bursts with various characteristics. The results of model simulation are presented. The prospects for applying the model to study the mechanisms of learning in neuronal cultures in vitro are discussed.

Keywords Neuronal culture · Modeling · Burst · Neuron model · Leaky Integrate-and-Fire

1 Introduction

Neuronal culture in vitro is available and convenient tool for studying mechanisms of interaction and synchronization of neurons in large populations [1]. Despite the large number of studies [2, 3], there is still no understanding of the nature of

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spontaneous synchronized population bursts that occur in the culture. Processes of their maintenance and evolution are also not investigated. Development of mechanisms for implementation of these processes and creation of a mathematical model adequate to a live culture in vitro, is of particular interest. Application of these mechanisms for solving some practical problems is not excluded.

Our purpose is to create a mathematical model of bursting activity of neuronal culture and to detect the parameters that affect its dynamic performance.

An important step is to choose the model of a neuron. LIF-neuron (Leaky Integrate-and-Fire neuron) is the most commonly used. Its dynamics in the interval between spikes is described by equation:

$$C_m \frac{du}{dt} = -(u - u_{rest})/R_m + I_{syn} + I_{ext}. \tag{1}$$

In Eq. (1), variable u represents the transmembrane potential; u_{rest} represents the rest potential; C_m and R_m denote membrane capacitance and resistance, respectively; I_{syn} and I_{ext} denote synaptic and external currents [1]. Neuron generates spike when potential u exceeds a certain threshold value.

Various modifications of the LIF-neuron are known, for example, Stabilizing Spiking neuron (SS neuron) [4]. We have also taken as a basis LIF-neuron, but attach new properties to this model that make it possible to regulate its own activity according to the external and internal factors.

We have refused a widespread model of long-term synaptic plasticity STDP [5, 6] and worked out a new learning rule for synaptic weights. The recurrent neural network with the proposed model of neurons shows activity in the form of synchronized bursts, as it occurs in neuronal cultures.

2 Neuron Model

We discuss the problem of creating a model of a system that produces synchronized spike activity of neurons. We believe that the simulation time is discrete with increments of 1 ms. Due to such problem statement, Eq. (1) for membrane potential in continuous time is converted to the form (2), in which the variable t denotes discrete time. In general terms, we obtain the following equation:

$$u(t+1) = \alpha\, u(t) + \beta\, (u_{rest} + u_{syn} + u_{ext}). \tag{2}$$

Parameter α depends on the relaxation time, $\tau_m = R_m\, C_m$; $\beta = 1 - \alpha$.

Denote potential of the i-th presynaptic neuron at the time t by $x_i(t)$, and synaptic weight—by $w_i(t)$. Then, the total contribution of all presynaptic neurons to the potential of the neuron concerned is estimated by the expression:

$$u_{syn}(t) = \sum_{i=1}^{n} w_i(t)\, x_i(t), \tag{3}$$

where n is the number of presynaptic neurons.

The fact of the spike from the i-th presynaptic neuron at the time t will be denoted by Kronecker delta function $\Delta_i(t)$. The number of spikes received from i-th presynaptic neuron in the time interval $[t{-}l,\ t]$, is calculated as follows:

$$h_i(t) = \sum_{\tau=t-l}^{t} \Delta_i(\tau). \tag{4}$$

The variable $h_i(t)$ will be further used to determine the long-term synaptic plasticity.

We introduce a new state variable of a neuron, which we call the neuron strength and denote by $s(t)$. The strength of a neuron describes its own activity and allows it to adapt to the changing activity of presynaptic neurons. At the start of modeling, it is recommended to set the initial value $s(0) = 1$. The minimum $s_{\min}$ and maximum $s_{\max}$ values of neuron strength are the parameters of the model that allow to regulate the frequency and duration of bursts.

Another new state variable $r(t)$ of a neuron represents its resource, which is needed to generate spikes. It is responsible for "fatigue" of the neuron. The resource is consumed every time a neuron gives the spike, and partially restores if there is no spike. When a resource is exhausted, the neuron loses the ability to produce spikes. Maximum of neuron resource depends on time and is proportional to neuron strength:

$$r_{\max}(t) = p \cdot s(t). \tag{5}$$

Neuron generates a spike $x(t) = s(t)$ at time t if neuron potential $u(t)$ exceeds a threshold value u_{thr}, and, moreover, at the same time resource is sufficient to generate a spike: $r(t) \geq r_{thr}$, where r_{thr} is a predetermined resource threshold.

If a neuron generates a spike, variables $s(t)$ and $r(t)$ change in accordance with the following expressions:

$$\begin{aligned} r(t+1) &= r(t) - 1; \\ s(t+1) &= s(t) + \frac{(s_{\max} - s(t))}{\tau_s} \frac{r_{\max}(t)}{r(t)+1}. \end{aligned} \tag{6}$$

Here, the parameter τ_s (model parameter) means relaxation time of the neuron strength. Its value should not be less than a few seconds.

When the spike-generation conditions fail, variables $s(t)$ и $r(t)$ evolve according to the following rule:

$$
\begin{aligned}
r(t+1) &= \begin{cases} r(t)\,(1+\frac{1}{r_{\max}(t)}) \text{ when } r(t+1) \le r_{\max}; \\ r_{\max} \text{ when } r(t+1) > r_{\max}; \end{cases} \\
s(t+1) &= s(t) + \frac{(s_{\min} - s(t))}{2\,\tau_s} \frac{r(t)+1}{r_{\max}(t)}\,.
\end{aligned} \tag{7}
$$

In accordance with Eqs. (6) and (7), the neuron strength increases if the spike occurred, and weakens—otherwise. Weakening of neuron strength proceeds in two times slower than its increase. This creates favorable conditions for learning and memory formation of neuronal culture.

Synaptic weight $w_i(t)$ of spike transmission from i-th presynaptic neuron to the considered neuron is adjusted each discrete time point under condition $\Delta_i(t) = 1$. Correction of synaptic weight $w_i(t)$ depends on many factors. We propose to carry out the correction in accordance with the following rule of long-term synaptic plasticity:

$$
\text{if } \Delta(t) = 1: \quad w_i(t+1) = w_i(t) + \frac{1}{\tau_w} \cdot \frac{(w_{\max} - w_i(t))}{w_{\max}} \cdot \frac{h_i(t)}{l}; \tag{8a}
$$

$$
\text{if } \Delta(t) = 0: \quad w_i(t+1) = w_i(t) + \frac{1}{q \cdot \tau_w} \cdot \frac{(w_{\min} - w_i(t))}{w_{\max}} \cdot \frac{l}{h_i(t)+1}. \tag{8b}
$$

Here, q is a model parameter, characterizing the rate of weakening of synaptic weight $w_i(t)$ during a long period of neuron activity absence. Factor $\frac{1}{\tau_w}$ affects the learning rate.

Thus, the proposed model of a neuron (1) has three state variables $u(t),\ r(t)$, and $s(t)$, which are described by a system of difference Eqs. (2)–(7), and (2) is characterized by the specific rule of self-learning of its synaptic weights (8a), (8b).

3 Neural Network Model

Model of neuronal culture is a recurrent neural network. Any two neurons form a unilateral synaptic connection with a given probability. Initial synaptic weights are set randomly. In the simplest case, which is considered in this work, the mutual spatial arrangement of neurons is not taken into account.

In real experiments, the activity of the neuronal cultures is registered using multi-electrode matrix. In the model, each electrode receives the signal from the randomly selected neurons with some randomly set weights.

Activity of the neural network is stimulated by internal noise—random spikes uniformly distributed in the space of neurons. The probability, with which a neuron fires spontaneously at any point in time, is a parameter of the algorithm.

The model takes into account delays in channels of spike transmission from neuron to neuron. The delay time is fixed for each channel, and is set randomly according to the normal probability distribution with parameters $\mu = 12$ ms, $\sigma = 3$ ms.

4 Modeling Results

We performed a simulation experiment, in which the network was composed of 100 neurons and 30 electrodes. Stimulating internal noise was 5 % (at each time step five randomly selected neurons generated spikes). Other model parameters were the following: $s(0) = 1$; $s_{\min} = 0.8$; $s_{\max} = 1.5$; $\tau_s = 20000$; $p = 7.5$; $w_{\min} = 0.2$; $w_{\max} = 1.5$.

Figure 1 shows an example of burst generated by the model. Burst duration was approximately 100 ms.

The graphs of population activity and the evolution of three state variables $u(t)$, $r(t)$, and $s(t)$ of one of the neurons is shown in Fig. 2. The horizontal axis represents the simulation time (ms). The length of realization is more than 1 s.

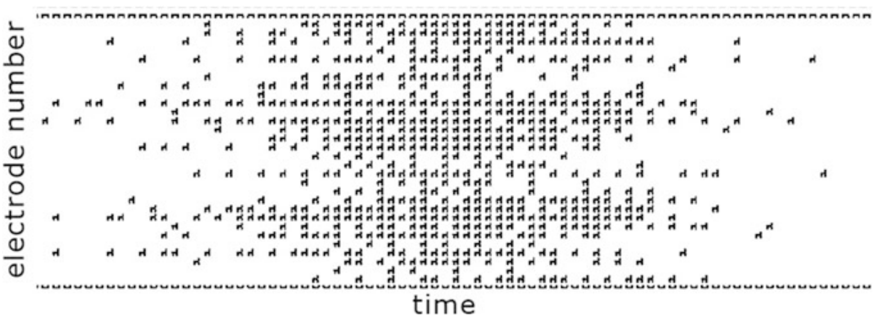

Fig. 1 Spatio-temporal pattern of bursting activity

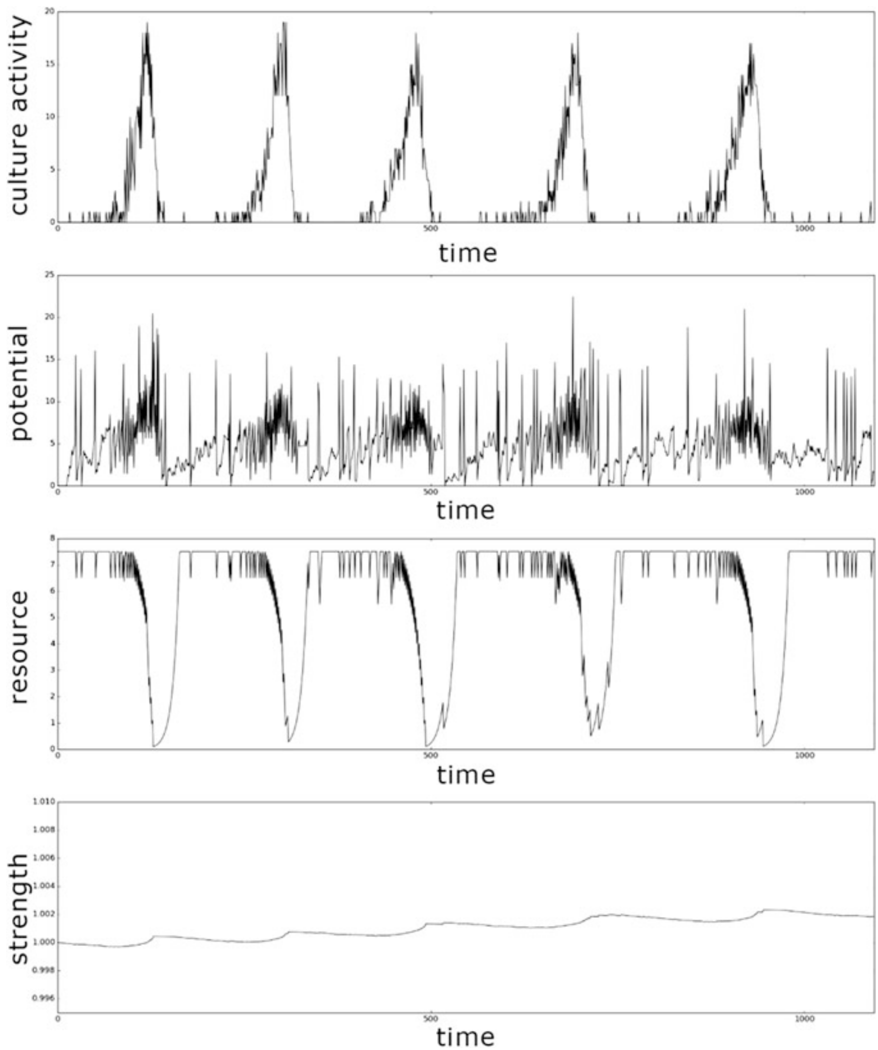

Fig. 2 The graphs of the basic processes in the model experiment: **1** population activity, **2** potential of a neuron, **3** neuron resource, **4** neuron strength

5 Conclusion

Model experiments show that the proposed mechanism of neuron functioning and self-learning provides the appearance and development of synchronized bursting in a recurrent network of interconnected neurons. Due to the parameter settings, neural network model makes it possible to obtain bursts of different duration and inter-burst-intervals. Different architectures of network and delays in channels of spike transmission cause the generation of bursts with various motifs and shapes of neuronal population activity.

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Dynamic Clustering of Connections Between fMRI Resting State Networks: A Comparison of Two Methods of Data Analysis

Victoria Zavyalova, Irina Knyazeva, Vadim Ushakov, Alexey Poyda, Nikolay Makarenko, Denis Malakhov and Boris Velichkovsky

Abstract In the present paper we describe an approach to the dynamical clustering of fMRI resting state networks and their connections, in which we use two known mathematical methods for data analysis: topological data analysis and k-means method. With these two methods we found about 4 stable states in group analysis. Dynamics of these states is characterized by periods of stability (blocks) with subsequent transition to another state. Topological data analysis method allowed us to find some regularity in subsequent transitions between blocks of states for individuals but it was not shown that the regularity repeats in all subjects. Topological method gives smoother distribution of dynamic states comparing to k-means method, highlighting about 4 dominant states in percentage, while k-means method gives 1–2 such states.

Keywords fMRI · Resting state · Independent component analysis · Correlation matrix · Dynamical network clustering · Topological data analysis

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1 Introduction

Researches of internal brain architecture based on fMRI studies of resting state or cognitive tasks do not pay sufficient attention to presence and importance of temporal variability. It is because the majority of existing approaches and algorithms to study functional connections implicitly assume that relationships between brain neural networks are constant throughout the experimental recording. In reality it is not true as modern studies show [1–3], the configuration of connections of networks changes in time. Research of these temporal changes can reveal more complex functional organization of human brain and explore it in dynamics.

In the present study human brain states were studied and categorized using topological data analysis and k-means method. In both methods, temporal dynamics of connections of independent components are found using ICA algorithm, then a set of all the temporal dynamics is divided on a large set of elementary states. In this set a small number of clusters (2–13) is selected, which then can be used as basic dynamical states characterizing general dynamics of behavior of network connections.

Recently, ideas from topological data analysis were adopted for brain network modeling [4]. In the concept of topological data analysis, changes of network states are explored with different thresholds. Under each threshold, binary networks are obtained for which topological features could be estimated; over the changing threshold, topological features also will be varying. It could be expressed in so called persistence curve, unique for each brain network. On the base of this curve, the clustering could be performed. In the case of k-means method, clustering is done on a small set of states having the highest dynamics, recorded on each subject; after that all other states are distributed among the found centers.

With these methods we explored not only variability of connections in time but also performed clustering of the network states by time. Results of these two methods are compared.

2 Methods and Materials

In the present study, 30 volunteers (10 women and 20 men in age of 21 to 35 years) were explored. Permission to conduct the experiment was obtained from ethics committee of IHNA RAS. Each of the volunteers gave an informed agreement to participate in the experiment. Subjects were at rest condition with closed eyes during the experiment. The experiment was performed on 3T MRI scanner Magnetom Verio installed in NRC Kurchatov institute. To obtain anatomical MRI images, 1-weighted sequence was used with the following parameters: 176 slices, TR = 1900 ms, TE = 2.19 ms and FOV = 250 $\times$ 218 mm^2. Functional MRI data were obtained with the following characteristics: 30 slices, TR = 2000 ms, TE = 25 ms, FOV = 192 $\times$ 192 mm^2, = 33 min.

fMRI signal was decomposed to independent components using ICA (Independent Component Analysis) by GIFT (Group ICA Of fMRI Toolbox), which allows to select functionally similar components (brain networks) with time dynamics. Also, this method gives the localization of spatial regions with the activity of independent components.

For dynamic networks obtained from fMRI data, 100 independent components were selected, and then this number was decreased to 50 by filtration, which was performed to eliminate artifacts determined by movements, physiological processes, or magnetic field. The filtration was performed using expert analysis. The 50 selected components were assigned to 7 large scale networks.

To evaluate dynamic variability of states, time series of analyzed components were divided by time on sections using a sliding window method with a step of 1 time sample. Next, for each window, correlation matrices were calculated. So, from a data array of $30 \times 50 \times 1000$ (number of subjects, number of components for each subject, size of time series for each dynamics) we derive a data array of $30 \times 50 \times 50 \times 979$ (number of subjects, size of correlation matrix [2 dimensions], number of time windows for each component). In total, for all the subjects, 29,370 correlation matrices were obtained.

3 Topological Method of Clustering. Persistent Homology for Brain Networks

Topological data analysis is fairly new, but already well-proven method for description of data structures. The theoretical ideas are fully described in the book of Edelsbrunner and Harer [5]. The big number of applications of topological ideas for brain data analysis could be found at Moo Chungs personal page (http://www.stat.wisc.edu/mchung/publications.html). In this work, an approach was used described in the paper [4]. The core idea is to construct nested sequences of increasing subsets. This process we call filtration. After that we are interested in the topological evolution of this filtration which could be expressed in so called homology groups or Betti numbers. The first three Betti numbers count the number of connected components, number of holes and voids. Usually these subsets are the simplicial complexes which are represented by the vertexes, edges and triangles. For analysis of the brain network it was suggested to use graph filtration [4]. Suppose that the measurement set is a set of time series $x = \{x_1, , x_{50}\}$.

It was assumed that each time series is normally distributed with zero mean and the unit variance. Distance $d_{(i,j)}$ was defined between the series x_i and x_j through the Pearson correlation: $d_{(i,j)} = 1 - corr(x_i, x_j)$. Then we introduce some threshold ε and connect the nodes with the edge if the distance $d_{(i,j)} > \varepsilon$. After that we obtain nested sequence of binary networks, which could be represented as graph sequences. These graph sequences could be described by the number of connected nodes in the graph for each threshold value which corresponds to Betti0 or a

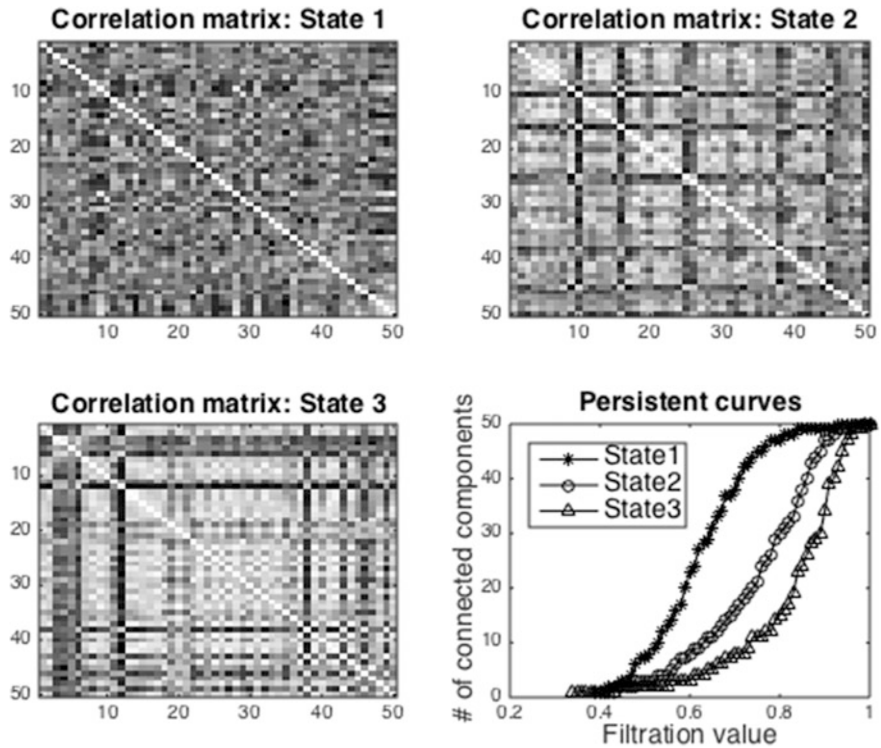

Fig. 1 Three different brain networks are presented with correlation matrices and persistent curves for them

number of connected components in algebraic topology. The speed of changes will depend on the structure of the network. If we plot the length of all the connected edges from the threshold, we will obtain persistent curve for brain network. The term persistent came from topology and means how the components persist with the condition changes. In case of threshold equal to 1, which corresponds to correlation above zero, all components in the graph will be connected, and graph minimal path length will be equal to the number of measurements, or independent component in our case. In case of threshold equal to 0, all the nodes will be disconnected, and path length will be also zero. The shape of the persistent curve significantly changes for different types of brain networks. At Fig. 1, the example of three different brain networks is presented with correlation matrices and persistent curves for them.

Applying this approach to analysis of our data of 50 selected components, we calculated persistent curves, which describe a particular correlation matrix. And then a set of the curves for all subjects was clustered. A stable number of clusters was not found, but all curves were clustered with k-means (L1 metrics) to 7 clusters (conditions), according to work of Allen et al. [1]. After analyzing all matrices of distances between curves, it became clear that there is not any general pattern for subjects. For one subject could present only two or three states, for other all range of states is presented. Also the states change in a step-like manner, and not chaotically.

As an alternative, we applied clustering using k-means method. From the 29,370 correlation matrices, 1500 matrices were selected to perform clustering (for each subject 50 matrices were selected by maximal dispersion of correlations). Usage of smaller numbers is problematic because the matrix itself in L1 norm (which we used for clustering) can be considered as a 2500 dimensional object. If the number of objects for clustering is too small, clustering results are unstable. To evaluate optimal number of clusters, we used a ratio of average intercluster distances to distances between clusters (global minimum should match optimal number of clusters) and Silhouette index. The criterion did not show optimal value, therefore, according to [1], we defined the number of clusters equal to 7. When centers of the 7 clusters were found, all the 29,370 correlation matrices were assigned to the clusters. For this operation we used L1 distance (Manhattan distance). Figure 2 shows 3 examples of the 7 cluster centers we found and statistics of their appearance for all the subjects.

Method of clustering based on k-means showed some instability of results. Depending on a set of subjects, clustering gives different results. Even a small change of the set of subjects could lead to change of cluster center position and, correspondingly, to change of state distribution. This instability occurred even with high number of iterations of the algorithm (experiments were performed with different number of repetitions, up to 600). However, 2–4 states were sufficiently

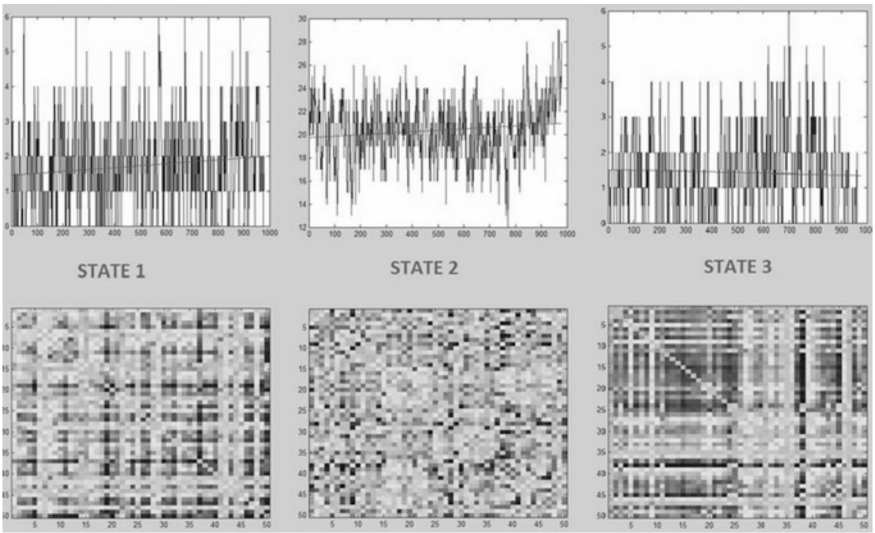

Fig. 2 Centers of the selected clusters and statistics of their appearance by time for all the 30 subjects. States 1, 2 and 3 are shown. Statistics diagrams show the number of subjects with the corresponding state by time

stable. Among selected states, 1–2 states are dominant (in percentage, they give $60-90\ \%$ among all detected occurrences). Up now, there is not any regularity of transitions between states identified using k-means method.

4 Results

Comparison of the two methods allows us to describe similarity and differences of the results they produce. At first, both methods find small number of relatively stable states (about 4 for group analysis). Second, both methods do not indicate regularity of transitions between states for group level. Third, topological method revealed some regularity of transitions between states for individuals, but both methods do not show significant regularity of transitions for all subjects. And forth, topological method gives smoother distribution of dynamic states comparing to k-means method, highlighting about 4 dominant states in percentage, while k-means method gives 1–2 such states.

5 Discussion

Both methods can be used and give reliable results for analysis of fMRI data. Topological data analysis was used for fMRI data clustering for the first time and gave interesting results. Comparison of the two methods of clustering presented in the article shows that the method based on topology can be used for dynamical clustering of network connections along with the k-means method. Comparison of quality of selected connections of fMRI resting state networks using these dynamical clustering methods will be done in future work. With respect to the quality, it should also be noted that both methods could be significantly improved by changing optional parameters, for example, choosing metrics for k-means method.

Analysis of distribution of states, obtained using k-means clustering for individual subjects showed that all the subjects are clustered well onto two groups. In the first group, there are subjects which have the dominant state for more than 80 % of states. In the second group, there are subjects which have the dominant state for less than 80 %. It could be supposed that the subjects having the dominant state for more than 80 % were at quiet wakeful or even at sleep onset condition.

Comparison of results of dynamical clustering of network connections obtained using presented methods with similar results obtained in the particularly relevant earlier work by Allen and Damaraju [1] shows a number of matches such as high correlation in visual cortex, dominance of one of the states over others, partial similarity of some states. At the same time several significant differences are observed: in the experiment performed in our work, the states do not let to cluster them in a stable way; dominance of one of the states is high (from 60 to 80 %) and does not give a clear picture, while in [1] the dominant state takes about 30 % of all states. One of the reasons of the difference could be a specificity of data acquisition.

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Neural Network Solution of an Inverse Problem in Raman Spectroscopy of Multi-component Solutions of Inorganic Salts

Alexander Efitorov, Tatiana Dolenko, Sergey Burikov, Kirill Laptinskiy and Sergey Dolenko

Abstract The paper presents a study into several aspects of solution of the inverse problem on determination of concentrations of components in a multi-component water solution of inorganic salts by processing Raman spectra of the solutions by perceptron type artificial neural networks. The studied aspects are: (1) determination of the optimal architecture of a multi-layer perceptron, (2) influence of the input dimensionality reduction by aggregation of adjacent spectral channels on the error of problem solution. The results are compared for two data arrays including spectra of solutions of: (1) 5 salts composed of 10 different ions (salt determination problem), and (2) 10 salts composed of 10 different ions (ion determination problem).

Keywords Inverse problem · Artificial neural network · Multi-layer perceptron · Raman spectroscopy · Multi-component solutions · Inorganic salts

1 Introduction

Operative control of the composition of water and water solutions is strongly demanded for environmental monitoring, in agricultural activity and industrial production. Modern methods of chemical analysis allow determining chemical composition with high accuracy, but they have serious drawbacks: need of laboratory processing of water samples with special reagents, and a long duration of

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each test. The methods based on measurement of the conductivity of solutions are more express, but they provide only the value of total salinity of water, and they are unable to detect existence of specific compounds and to determine their concentrations.

The authors of [1–4] suggested determining the concentrations of salts dissolved in water using changes of characteristics of Raman spectra. These approaches provide express remote determination of concentration of individual ions (or salts). As known [2, 5, 6], Raman spectra are highly sensitive to various types and concentrations of dissolved ions: complex ions (such as SO_4^{2-}, NO_3^-) have proper bands in the area around 1000 cm^{-1}, and all solutes influence the shape and position of water Raman valence band. If the solution consists of several components, there are nonlinear interactions affecting the shape of the spectrum; therefore, there is no simple analytic model for solving the inverse problem (IP) in a multi-component solution.

The authors of this study suggested and developed the method of using the artificial neural networks (ANN) to determine the concentrations of salts [7–9] and ions [10, 11] in multicomponent water solutions. ANN are gaining popularity in solving complex multi-parameter problems, including environmental monitoring of natural waters [12–14], determining the salinity of sea water [15] and metal ions in industrial waters [16, 17].

2 Data Preparation

The first IP was solved for 5 inorganic salts: NaCl, NH_4Br, Li_2SO_4, KNO_3, CsI. The data array consisted of 9144 Raman spectra for known salts concentrations in water solutions. As all 10 ions were different, the concentrations on an anion and its corresponding cation always had the same ratio, making it possible to speak of salts concentrations in spite of the fact that in all solutions the salts were fully dissociated.

Initially, each band of the Raman spectrum was recorded into the range 1024 spectral channels wide, in the frequency range 200–2300 cm^{-1} for the low frequency band, and 2300–4000 cm^{-1} for the valence band. For further processing, more narrow informative ranges were selected: 766 channels in the range 281–1831 cm^{-1} for the low frequency band, and 769 channels in the range 2700–3900 cm^{-1} for the valence band.

The second IP was solved for 10 ions (Mg^{2+}, Li^+, NH_4^+, K^+, Na^+, SO_4^{2-}, NO_3^-, Cl^-, F^-, HCO_3^-). The obtained data array consisted of 4445 Raman spectra for known salts concentrations in water solutions. Every ion was contained in two of the inorganic salts, which were used in preparing the solutions: KF, $KHCO_3$, LiCl, $LiNO_3$, $MgSO_4$, $Mg(NO_3)_2$, NaCl, $NaHCO_3$, NH_4F, $(NH_4)_2SO_4$, so the concentration of each anion was not bound to the concentration of any cation. Every spectrum had 1824 channels in the frequency range 565–4000 cm^{-1}.

In both problems salt concentrations didn't exceeded the limit of solubility for each specific combination of salts. The data array was randomly divided into training, test (used to determine the moment to stop training), and examination (out-of-sample) sets in the ratio of 70:20:10, respectively. 5 equal neural networks (multi-layer perceptron, MLP) were trained with different initial weight values, and the results of their application were averaged, to eliminate the influence of the initial MLP weights choice.

3 Results

At the first phase of the study, we needed to choose the best architecture of MLP. The choice of some parameters was based on experience of solving the problem for 5-component solutions: learning rate 0.01; momentum 0.5; stopping criterion—1000 epochs after the minimum error on the test data set. However, the depth of the MLP and the number of neurons in the hidden layers (HL) had to be chosen specially for each problem.

In the experiments, 8 ANN were checked: 3 MLP with a single HL (having 32, 64, 80 neurons); 3 MLP with two HL (having 32 + 16, 64 + 32, 80 + 40 neurons in the 1st and the 2nd HL, respectively; 2 MLP with three HL (having 64 + 32 + 16 and 40 + 20 + 10 neurons for the IP of 5 salts, 64 + 32 + 16 and 48 + 24 + 12 neurons for the IP of 10 ions, in the 1st, 2nd and 3rd HL, respectively). Figures 1 and 2 present the values of the coefficient of multiple determination R^2 on the examination set averaged over all salts for the first IP and over all ions for the second IP, characterizing the accuracy of concentrations determination.

The best result for the IP of 10 ions was achieved by the largest MLP with 3 HL. For the IP of 5 salts, the results are much better, and there is no pronounced dependence on MLP architecture; there is no need to use 3 HL. The obtained results

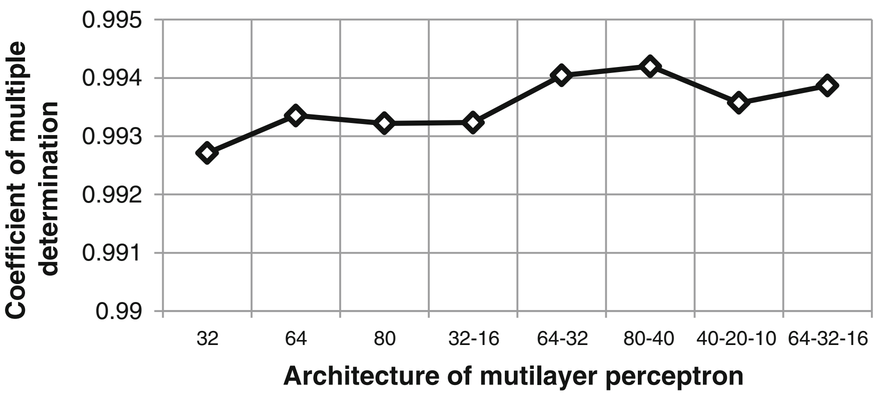

Fig. 1 The dependence of the coefficient of multiple determination R^2 on the examination set (averaged over ANN outputs) on the architecture of the multilayer perceptron (the number of neurons in HL are listed in the signatures of the horizontal axis) for the IP of 5 salts

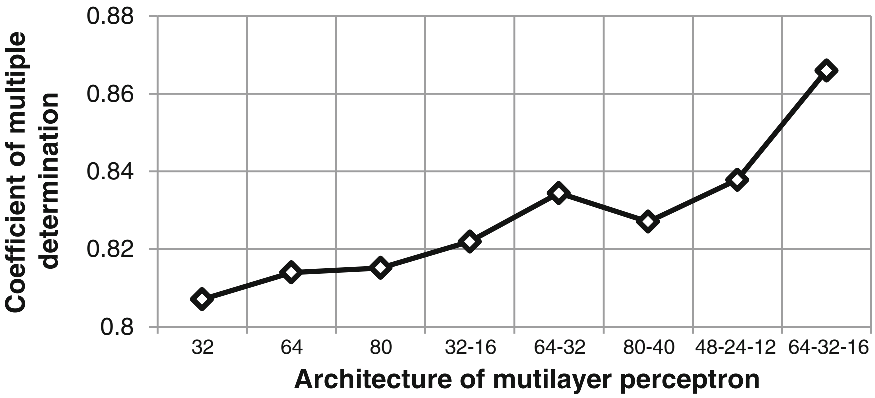

Fig. 2 The dependence of the coefficient of multiple determination R^2 on the examination set (averaged over ANN outputs) on the architecture of the multilayer perceptron (the number of neurons in HL are listed in the signatures of the horizontal axis) for the IP of 10 ions

are quite expected: the IP for 10 ions is much more complicated, and the data represents stronger nonlinear interactions than for the IP of 5 salts, requiring a much more complex MLP architecture to solve the problem.

Next, the dependence was considered for each ion separately. The choice of the largest MLP demonstrates the best results for 7 ions out of 10. For Mg^+, Li^+, and SO_4^{2-}, the best results are provided by the MLP with 2 HL having 64 and 32 neurons. Also it should be noted that for NO_3^- and NH_4^+, the architecture doesn't have essential significance.

In the second part of this study, we studied the possibility of improving the quality of IP solution by decreasing the number of input features using averaging of the intensity values of adjacent spectral channels. First, it would mathematically simplify the task by reduction of the input dimensionality; second, it would eliminate some noise in the data. On the other hand, aggregation inevitably leads to loss of some information that may be useful. Figures 3 and 4 present the dependence of the quality of the IP solution (mean absolute error in M) on aggregation fold (the number of averaged channels), on the examination set.

We investigated the influence of dimensionality reduction with aggregation fold of 2, 4, 8, 12, 16, 24, 32, for the problems of determination of salts and ions concentration by the MLP with architectures chosen in the first part of this study. The dependence of the mean absolute error value in M on the aggregation fold averaged over all ANN outputs for the IP of salts is presented in Fig. 3. This approach, particularly, implementation of 8-fold aggregation for the inverse problem of determining concentrations of 5 inorganic salts, allowed more than 13.4 % improvement of the result, relatively to the solution using the full-dimension data.

Expectedly, for the problem of 10 ions the behavior of the mean average error is completely different than that for the problem of salts (Fig. 4). Only 2-fold aggregation has positive influence on the results. Probably this is due to the fact that

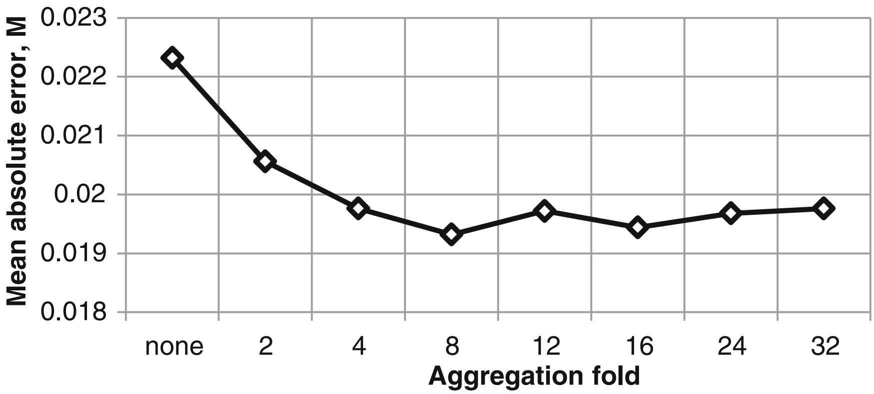

Fig. 3 The dependence of mean absolute error of determination of salts concentrations on the examination set (averaged over ANN outputs) on aggregation fold (the number of aggregated adjacent channels) for the IP of 5 salts

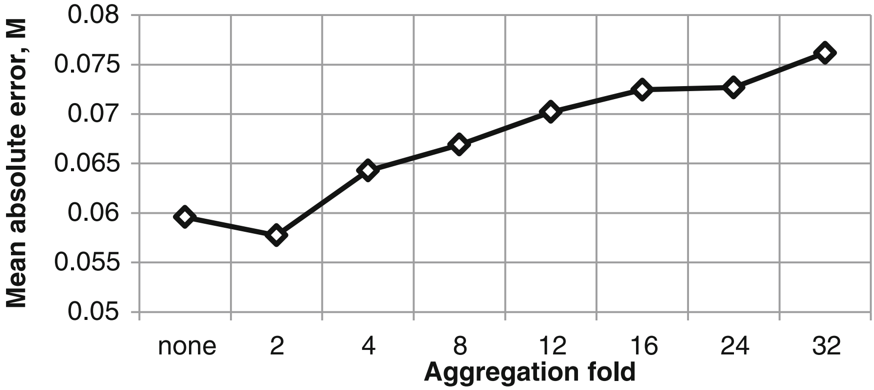

Fig. 4 The dependence of mean absolute error of determination of ions concentrations on the examination set (averaged over ANN outputs) on aggregation fold (the number of aggregated adjacent channels) for the IP of 10 ions

this problem is more complicated, and when the concentrations of all 10 ions are found separately, this requires simultaneous analysis of various parts of the spectrum, and higher input dimensionality is needed.

Next, the results were considered separately for each ion. Implementation of 2-fold aggregation improved the results of determination of concentrations for 8 ions of 10. The most significant improvement (12.5 %) was achieved for NH_4^+; for HCO_3^- the improvement was greater than 9.9 %; for NO_3^-, F^-, SO_4^{2-}—greater than 7 %. At the same time, deterioration of the results was observed for Li^+ and Na^+, for 9.2 and 2.1 %, respectively.

4 Conclusion

Comparison of the results for the inverse problems of 5 salts and 10 ions shows that the more complicated problem of 10 ions requires a more complex and deeper MLP architecture. Aggregation is much more efficient for the simpler problem of 5 salts.

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Prediction of Relativistic Electrons Flux in the Outer Radiation Belt of the Earth Using Adaptive Methods

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Abstract Prediction of the time series of relativistic electrons flux in the outer radiation belt of the Earth encounters problems caused by complexity and nonlinearity of the “solar wind—the Earth’s magnetosphere” system. This study considers such prediction by the parameters of solar wind and interplanetary magnetic field and by geomagnetic indexes, using different methods, namely, Artificial Neural Network, Group Method of Data Handling and Projection to Latent Structures (also known as Partial Least Squares). Comparison of quality indexes of predictions with horizon from one to twelve hours among each other and with that of trivial model is presented.

Keywords Time series · Prediction · Prediction horizon · Earth’s magnetosphere · Relativistic electrons of the outer radiation belt of the Earth · Committee of predictors · Group method of data handling · Projection to latent structures

1 Introduction

The Earth’s Radiation Belts (ERB) are inner zones of the Earth’s magnetosphere, in which charged particles—electrons, protons, alpha particles—are held by the geomagnetic field, which is close to dipolar. As a first approximation, ERB is a toroid in which it is possible to distinguish two areas—inner and outer radiation

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belts with a gap between them. The outer ERB is very unstable: its relativistic electrons (RE) flux may change for an order of magnitude and more within several hours, and the location of its maximum and boundaries may also change significantly [1]. It is a complex dynamic system, the state of which can change much, depending on the values of the components of interplanetary magnetic field (IMF), on solar wind (SW), and on geomagnetic disturbances. The main reasons of these variations are not understood yet. It is clear that processes of both acceleration and losses are responsible for formation of ERB. But it is possible that the same physical processes under different conditions can cause both.

The processes in the outer ERB most likely have nonlinear character. Thus, instant state of the outer ERB is not completely determined by instant values of external parameters, and the duration of "memory" and relaxation processes for ERB is not constant.

Relativistic electrons of the outer ERB are sometimes called "killer electrons", as they are very dangerous for electronic devices onboard spacecraft, and may cause breakdown of their normal operation [2]. Therefore, possible prediction of the reaction of the outer ERB to changes of the physical parameters of IMF and SW is important.

Significant variations of RE flux in the outer ERB are observed during geomagnetic disturbances (magnetic storms), caused in turn by disturbances of IMF and SW. As a rule, RE flux falls sharply during the main phase of a magnetic storm. During the recovery phase, approximately in half of the cases there is an increase of RE flux to a level significantly exceeding that before storm [1].

High correlation among RE fluxes at geosynchronous orbit, SW speed and other parameters was described back in 1979 [3]. Experimental values of electron flux, which the prediction is compared to, are obtained in the experiment at spacecraft of Geostationary Operational Environmental Satellite (GOES) series [4].

In the paper of Baker et al. [5], it was shown that integral day values of the flux of electrons with energy >2 meV, measured at geosynchronous orbit, can be predicted one day ahead, using a linear filter with SW speed at the input. Later on, his ideas were developed in elaboration of Relativistic Electron Forecast Model (REFM) [6].

An alternative approach to prediction of RE fluxes in the outer ERB is based on use of artificial neural networks (ANN). This approach is used in the models presented in [7, 8] to predict RE flux at geostationary orbit.

In this study, perceptron type Artificial Neural Network, Group Method of Data Handling, and the method of Projection to Latent Structures (also known as Partial least Squares method) are used for prediction of hourly average values of RE flux in the outer ERB with prediction horizon from one to twelve hours.

2 Data Sources and Preparation

Time series (TS) of hourly values of the following physical quantities were used as input for all the prediction algorithms:

(a) SW parameters in Lagrange point L1 between the Earth and the Sun: SW speed v (measured in km/s) and SW protons density n_P (measured in cm^{-3}).
(b) IMF vector parameters in the same Lagrange point L1 (measured in nT): B_x, B_y, B_z (IMF components in GSM system) and B amplitude (IMF modulus).
(c) Geomagnetic indexes: equatorial geomagnetic index Dst (measured in nT) and Global geomagnetic index Kp (dimensionless).
(d) Flux of relativistic electrons with energies >2 meV at geostationary orbit (measured in $(cm^2 \cdot s \cdot sr)^{-1}$).

The specific sources of data are listed elsewhere [9].

A distinctive feature of relativistic electrons flux as a TS is the wide dynamical range of its values, covering more than 6 orders of magnitude. As a rule, in such situations the value is transferred to logarithmic scale, to level out relative prediction errors in different orders of magnitude. In this study, comparison of statistical indexes of error, data interpolation and algorithms adjustment were carried out in logarithmic scale. Our preceding studies showed that in this case the prediction errors are lower than in the case when no transfer to the logarithmic scale is performed.

Besides that, to account for daily and yearly variations of the predicted quantity, TS of sine and cosine values with daily and yearly period were also used as input data. To account for the previous history of input features, delay embedding of all TS for 24 h depth was used, in two ways discussed below.

Delay embedding significantly increases the negative influence of data gaps on data volume and representativity. Therefore, in this study we used filling of gaps 12 or less hours long by linear interpolation (for time moments when the gap is already over) or by extrapolation of the latest known value. Such method of gap filling is based on the fact that rapid changes are not typical for virtually all kinds of data used. Also, there is no reason for use of more sophisticated estimates.

As the learning sample for all the three adaptive algorithms, the data from October 22, 1997 till December 31, 2009 (about one full solar cycle), was used. After delay embedding, the learning sample was divided into training set and test set in the ratio of 75/25 by random selection of patterns. As out-of-sample data, the examination set from January 1, 2010 till March 31, 2015 was used to test the obtained predictors.

3 Used Methods and Their Parameters

The ANN architecture used in the present study was the multi-layer perceptron (MLP). Special attention has been paid to the number of hidden layers (HL) of the MLP, and to the number of neurons in the HL. A simple perceptron without HL performed much worse than the single HL MLP. MLPs with 2 and 3 HL failed to provide any substantial improvement in the performance as compared to the single HL MLP.

Due to the stop training criterion used (500 epochs since minimum error on the test set of data), the performance of the MLPs remained practically unchanged in a wide range of the number of neurons in the hidden layers.

Eventually, the selected ANN architecture was MLP with 32 neurons in the single hidden layer, tanh activation functions, trained by standard error backpropagation with learning rate 0.01 and moment 0.5.

In each experiment, 3 MLPs were trained, differing only by weights initialization and by the seed of random presentation of the patterns. The 3 ANN obtained formed a simple committee, whose answer was formed as the average among the answers of all the networks. There were no grounds to introduce more complex weighting rules. Note that in all cases the statistical indexes of the average turned out to be somewhat better than those of each of the predictions of separate networks, thus confirming the fact that even a committee of similar predictors on a sufficiently large data array has advantage against separate predictors. The standard deviation of the averaging was small in all cases (less than 1 % of the average itself), thus confirming weak dependence of the result on initial conditions of ANN training.

Group Method of Data Handling (GMDH) is a biologically inspired method for building complex polynomial-based regression models, using incremental increase in model complexity, model combinations and selection of the fittest [10]. This study used the implementation of GMDH in GMDH Shell software package [11], in two modes—Combinatorial and GMDH neural network. Combinatorial GMDH always performed better for this problem; so all the results presented here are for this mode.

The essence of the PLS method [12] is interdependent decomposition of matrices X (the matrix of inputs) and Y (the matrix of outputs) according to the principle of principal component analysis (PCA). In PLS, interconnection of the matrices X and Y during formation of the vectors of loadings (the basis of principal component space) is taken into account. Based on the latter, the matrix of regression coefficients Y = XB, which provides solution of the problem, is created.

While delay embedding allows taking into account the preceding values of the inputs, it provides a drastic increase in the number of inputs, hampering the situation for nearly all prediction methods. To make things easier, in this study we used a thinned set of the delays (1, 2, 3, 4, 6, 9, 12, 16, 20, 24 h) for GMDH, PLS, and what we call ANN-1. For comparison, we also used ANN-2 with the same parameters, but which was trained on the full set of the delays from 1 to 24 h.

4 Results and Discussion

Figure 1 displays the values of multiple determination coefficient R^2 and the root mean squared error (RMSE), measured in orders of magnitude of electron flux, as functions of prediction horizon (from 1 to 12 h) for the average of predictions of 3

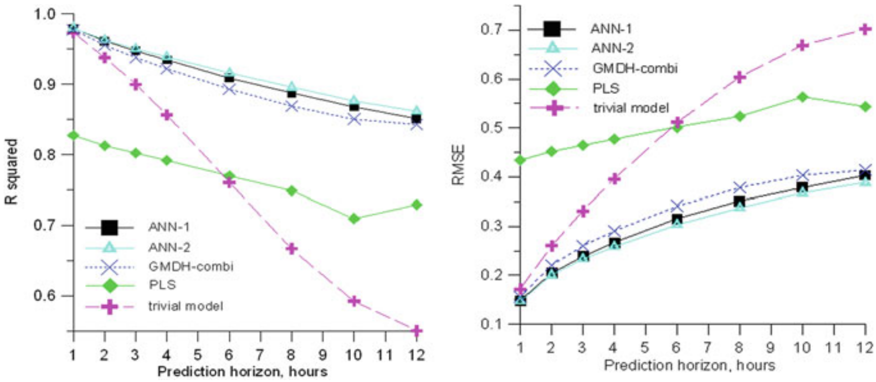

Fig. 1 R^2 and root mean squared error versus prediction horizon in hours

ANN with different sets of initial weights (ANN-1 and ANN-2 as described above), Combinatorial GMDH, PLS and for the trivial model (prediction = latest value).

Figure 2 displays an example for comparison of measured and predicted time series of decimal logarithm of electron flux (for the period from day 44 to day 53 of 2015). The thick solid line corresponds to the measured time series, all the other lines represent predictions with various prediction methods.

The following observations and conclusions can be made.

1. Among the methods tested in equal conditions (with the thinned delay set), the best results are provided by ANN-1. Combinatorial GMDH performs slightly worse. PLS gives much worse results, for horizons less than 6 h even worse than the trivial model. This can be explained by the fact that PLS is a linear method using all the input features. Combinatorial GMDH in this study provided models that were also linear, but it selected only a limited set of the most appropriate input features. Conversely, perceptron type ANN is a universal non-linear approximator.
2. Comparison of ANN-1 and ANN-2 (Fig. 1) shows that thinning the set of the delays makes the ANN perform slightly worse. This is partly compensated by faster training. Obviously, equal thinning of the delays for all the physical quantities should be changed to directed selection of significant input features.
3. Prediction quality monotonously decreases with increasing prediction horizon. However, no drastic decrease of ANN prediction quality is observed when the horizon is increased from 1 h to 12 h. Further increase of the horizon should be tested.
4. In Fig. 2 it can be seen that the predicted time series has a pronounced daily cycle, well reproduced by all models based on the values of sine and cosine with daily period, fed to the inputs of all the algorithms. The errors of the models are mostly observed at the lowest values of the electron flux (where the measured values are less reliable), and in the vicinity of minima and maxima of the daily cycles.

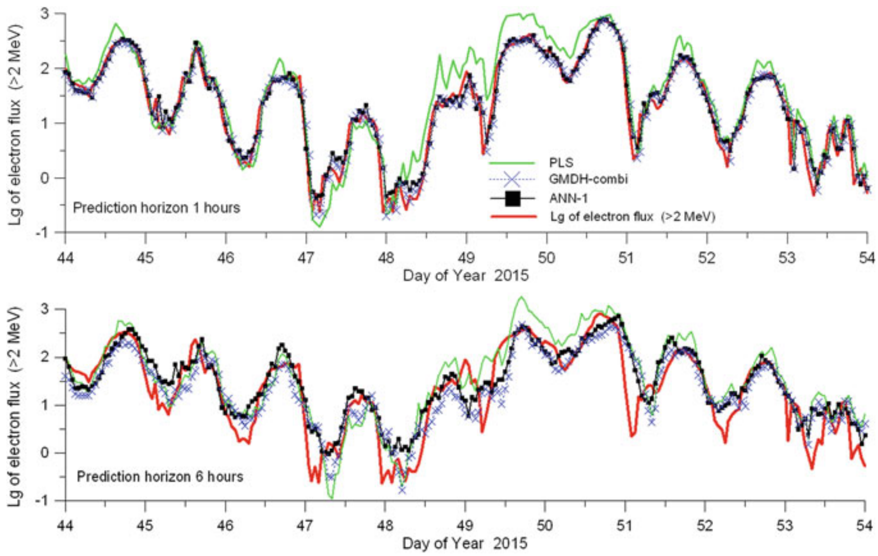

Fig. 2 Comparison of measured and predicted values of the logarithm of electron flux

5). It could be expected that creating a committee of predictors of various nature would allow increasing the prediction quality. However, simple averaging of the predictions of ANN, GMDH, and PLS performs significantly worse than ANN alone. Excluding PLS gives a prediction model whose performance is somewhat better than that of only ANN, but the improvement is negligible. Predictor weighting, with weights, determined by the quality of separate predictors on training set, brings improvement that is still insignificant. Possible reason is that the combined predictors are not statistically independent, so they make errors on the same samples. The other possible reason may be low predictability of the target TS in the whole, or lack of some informative input features. Elaboration of the most adequate input feature set (including the delays used in embedding) should be included in the following studies.

5 Conclusions

This paper describes the solution of the problem of prediction of the outer Earth's radiation belt relativistic electrons flux with adaptive methods. The compared methods are perceptron type Artificial Neural Networks, Group Method of Data Handling, and method of Projection to Latent Structures (Partial Least Squares).

The best performance is demonstrated by an average of outputs of three ANN trained with various sets of initial weights. It has been shown that with increasing prediction horizon from 1 to 12 h, the decrease in its quality is not too dramatic, allowing one to raise the issue of further increase of the prediction horizon. The directions for further improving the quality of the prediction include significant feature selection and using a committee of statistically independent predictors.

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Comparative Analysis of Residual Minimization and Artificial Neural Networks as Methods of Solving Inverse Problems: Test on Model Data

Igor Isaev and Sergey Dolenko

Abstract This study compares perceptron type neural network and residual minimization for solving inverse problems, at the example of a model inverse problem. Stability of both methods against noise in data was investigated. The conclusion about limited applicability of residual as a criterion of the solution quality has been made.

Keywords Artificial neural networks · Perceptron · Inverse problems

1 Introduction

Inverse problems are an important class of problems. Almost all problems of indirect measurements can be attributed to one of them. These include many problems from the domains of geophysics [1], spectroscopy [2], various types of tomography [3], and many others.

In practical tasks it is often necessary to find the distribution of some parameter in one area of space by features measured in another area of space. As a rule, the degree of influence of the parameter on system response depends on the location of the node described by the parameter, and it decreases with distance from the node to the detector, which corresponds to many types of interactions.

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Among such tasks is the inverse problem of magnetotelluric sounding, where one has to find the distribution of conductivity in the thick of the Earth by the components of electromagnetic field measured on its surface [4, p. 157]. Due to shielding of the underlying layers by the overlying ones, the contribution of the deep layers is small.

In general case, such problems have no analytical solutions; therefore, the traditional methods to solve them are optimization methods based on repeated solution of the direct problem with minimization of residuals [4, p. 158], or matrix-based methods using regularization by Tikhonov [5, p. 304].

Optimization methods have several drawbacks such as high computational cost when applied and, accordingly, low operation speed, the need for good first approximation, and, most importantly, the need to have a correct model for solving the direct problem. For methods based on regularization, the main difficulty is the necessity to choose a regularization parameter.

In this study we consider neural networks as an alternative method of solving various inverse problems [6–8] that is free from these shortcomings.

Neural network solution and the solution obtained by minimizing the residual are compared on a simple model problem introduced in [9]. As the model problem is free from additional factors present in real world inverse problems studied by the authors before (e.g. [10, 11]), this allows us to clear out the effects inherent for neural networks as a method of solving inverse problems.

2 Numerical Experiment

Let us define the inverse problem with the help of a simple polynomial model with coefficients a_{ij}, b_{ij}, c_{ijk}, d_{ij}, e_i, where each "observed feature" $x_1 \ldots x_5$ depends on all "determined parameters" $y_1 \ldots y_5$ by the formula:

$$x_i = \sum_{j=1}^{5} a_{ij} \cdot y_j^3 + \sum_{j=1}^{5} b_{ij} \cdot y_j^2 + \sum_{j=1}^{5} \sum_{k=j+1}^{5} c_{ijk} \cdot y_j \cdot y_k + \sum_{j=1}^{5} d_{ij} \cdot y_j + e_i$$

The dependence of the impact of a parameter on its "location" is set using the dependence of the coefficients on the conventional "distance" from inputs to outputs (Fig. 1a). In the present study, the inverse proportionality to the square of the distance, widespread in nature, was used:

$$f_{ij} = \frac{1}{r_{ij}^2} = \frac{1}{i^2 + j^2}$$

Coefficients a_{ij}, b_{ij}, c_{ijk}, d_{ij}, e_i accepted random values proportional to the given dependence:

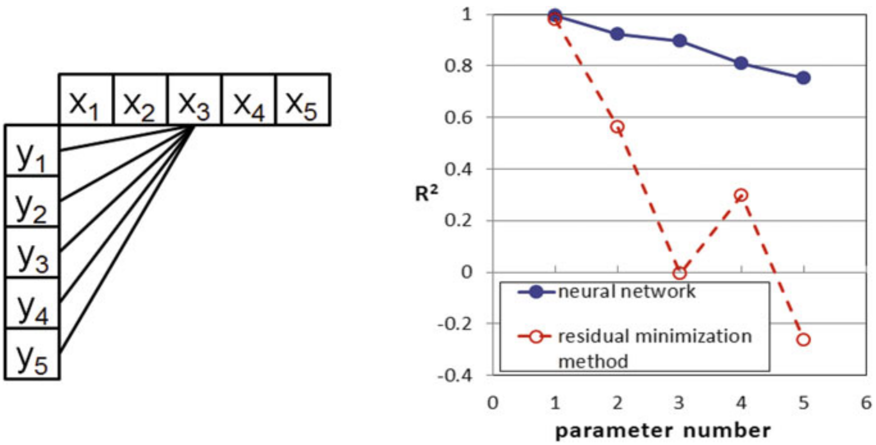

Fig. 1 **a** Layout of connections of the features; **b** dependence of problem solution quality (R^2) on the number of determined parameter

$$a_{ij} \sim b_{ij} \sim d_{ij} \sim f_{ij}$$

$$c_{ijk} \sim \frac{f_{ij} + f_{ik}}{2}$$

$$e_i = \sum_{j=1}^{5} f_{ij}$$

The determined parameters y_1 … y_5 took random values from 0 to 1.

These formulas were used to generate data sets containing 3000 patterns, divided into training, test, and examination sets with the ratio of 70, 20, and 10 %, respectively.

The neural network (NN) was used as follows. Training was performed on the training data set. To prevent network overtraining, the test set was used (training was stopped after 500 epochs without improvement of the result on the test set). Out-of-sample evaluation was performed on the examination set. Each determined parameter was calculated separately from all the rest. Thus, each NN had 5 inputs and 1 output. To solve this problem, we used perceptrons with 3 hidden layers containing 16, 12, 8 neurons. Hidden layers used the sigmoid transfer function; the output layer used a linear one. For each determined parameter, 5 networks were trained with various weights initializations. The statistics of the 5 networks were averaged.

For the residual minimization method (RMM), the exact model (type of the polynomial and its coefficients) was considered to be known. Through simultaneous selection of the parameters y_1 … y_5, the residual between the true values of the features x_1 … x_5 and those calculated by solving the direct problem was minimized.

For this purpose, the non-linear method of generalized reduced gradient [12] implemented in Microsoft Excel was used. Calculation was performed separately for each pattern in the examination set, and then the statistics over the whole data set were calculated.

For the results of application of each method, the coefficient of multiple determination R^2 between the desired and obtained values of the parameters was calculated, as well as the average residual between the values of the features observed and calculated through the solution of the direct problem.

A graph of R^2 *versus* parameter number is shown in Fig. 1b. It is easy to notice that RMM performs much worse than NN; to determine the parameters y_3, y_4, y_5 it is practically inapplicable. It should be noted that the average residual value for RMM was equal to 0.00017, while for NN solution it was an order of magnitude higher: 0.00158.

3 Stability of the Methods Against Noise in Data

NN trained on the data of the model problem without adding noise were applied to examination data sets containing noise of various types and levels. RMM based on the exact model of solution of the direct problem was applied individually to each pattern of the data sets with noise.

Two types of noise were considered: additive and multiplicative, and two kinds of statistics: white noise (uniform distribution) and Gaussian noise (normal distribution). The value of each observed feature was transformed as follows for additive Gaussian, additive white, multiplicative Gaussian, and multiplicative white noise, respectively:

$$x_i^{agn} = x_i + norminv(random, \mu = 0, \sigma = noise\,level) \cdot \max(x_i)$$

$$x_i^{awn} = x_i + (1 - 2 \cdot random) \cdot noise\,level \cdot \max(x_i)$$

$$x_i^{mgn} = x_i \cdot (1 + norminv(random,\ \mu = 0, \sigma = noise\,level))$$

$$x_i^{mwn} = x_i \cdot (1 + (1 - 2 \cdot random) \cdot noise\,level))$$

Here *random* is a random value in the range from 0 to 1, *norminv* function returns the inverse normal distribution, $\max(x_i)$ is the maximum value of the given feature over all patterns, *noise_level* is the level of noise (the considered values were: 1, 3, 5, 10, 20 %).

From Fig. 2b, c it can be seen that RMM shows greater immunity to noise for the "upper" parameters y_1 and y_2, demonstrating a lower degradation rate. However, for "deeper-lying" parameters it is inapplicable (Fig. 2d). In the presence of noise, in the space of observed features RMM also provides significantly lower residual values than NN (Fig. 2a).

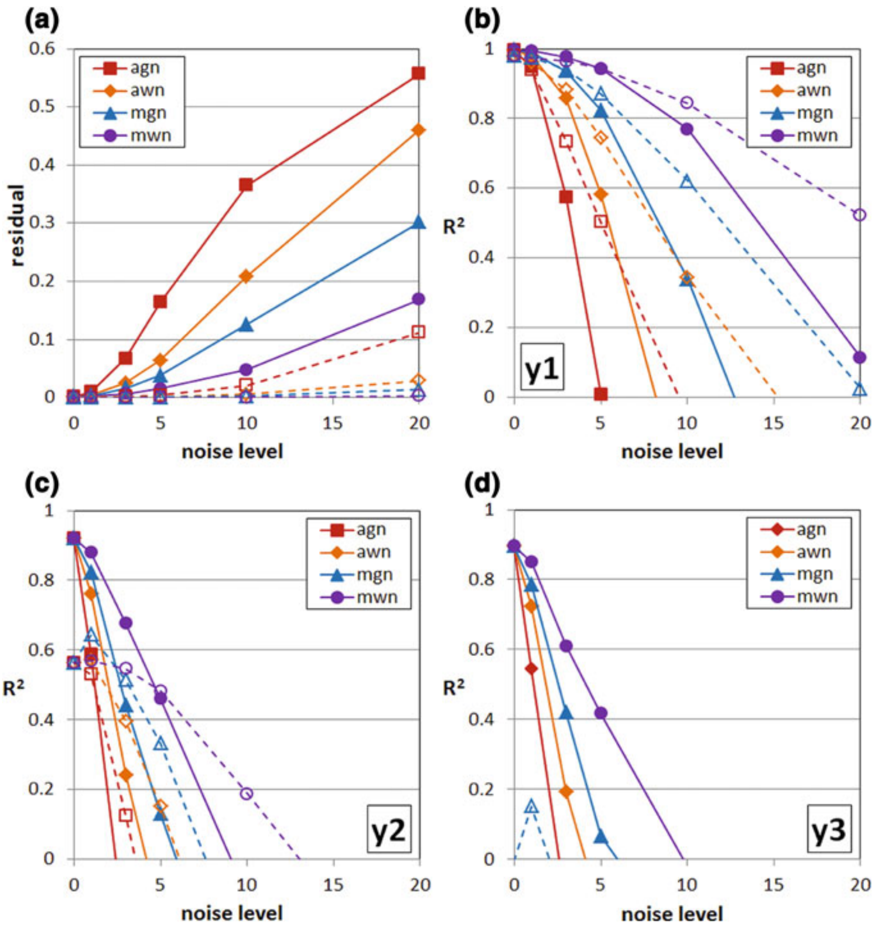

Fig. 2 The dependence of the residuals (**a**) and coefficient of multiple determination R^2 for determined parameters y_1, y_2 and y_3 (**b**, **c**, **d**) on the level and type of noise in the examination set for NN solutions (*solid line*) and for RMM solutions (*dashed line*)

4 Comparison of Solution Evaluation Criteria

For the solution of the inverse problem on noiseless and noisy data, Fig. 3 plots the residual values calculated on the set of parameters $y_1 \ldots y_5$ obtained by NN and RMM, *versus* coefficient of multiple determination R^2 calculated individually for each parameter. Each point on the plots corresponds to some dataset with specific noise level and type, for NN—also for one specific set of networks (containing networks for all determined parameters) out of 5 sets with various weight initializations.

Figure 3 clearly shows that the small values of the residual in the space of the observed features do not mean exact solution of the inverse problem: for the

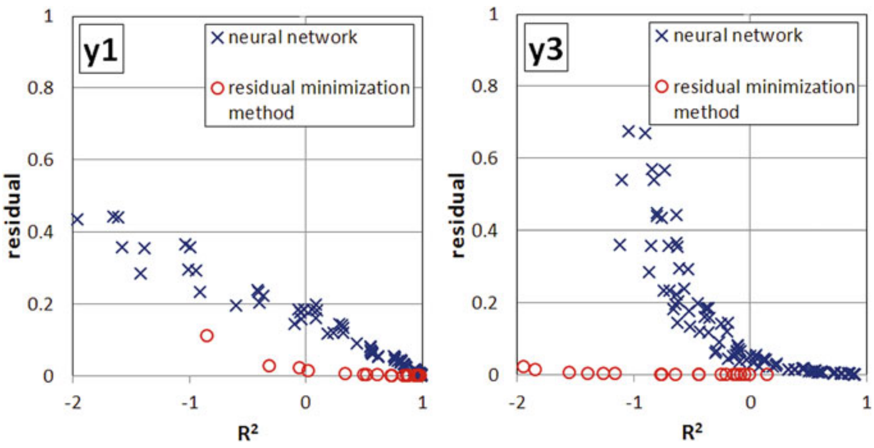

Fig. 3 Residuals obtained on the calculated set of parameters *versus* the coefficient of multiple determination R^2 for parameters y_1 and y_3, for NN and RMM solutions

solutions found with RMM, small values of the residual may correspond to negative values of R^2 in the parameter space. Unlike RMM, NN is trained minimizing the error directly in the parameter space; as a result, the small values of residuals for NN solutions in the space of observed features correspond to low error of inverse problem solution in the space of parameters. At the same time, in both cases (for NN and for RMM) a large residual means that the solution of the inverse problem in the space of parameters is unsatisfactory.

5 Conclusion

Neural networks demonstrate better results for solution of inverse problems, however, possessing somewhat smaller noise immunity.

Low residual value in the space of observed features cannot be used as a sufficient condition of good solution quality in the space of determined parameters, but it is a necessary condition for it.

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A Biologically Inspired Architecture for Visual Self-location

Helio Perroni Filho and Akihisa Ohya

Abstract Self-location—recognizing one's surroundings and reliably keeping track of current position relative to a known environment—is a fundamental cognitive skill for entities biological and artificial alike. At a minimum, it requires the ability to match current sensory (mainly visual) inputs to memories of previously visited places, and to correlate perceptual changes to physical movement. Both tasks are complicated by variations such as light source changes and the presence of moving obstacles. This article presents the Difference Image Correspondence Hierarchy (DICH), a biologically inspired architecture for enabling self-location in mobile robots. Experiments demonstrate DICH works effectively despite varying environment conditions.

1 Introduction

Self-location (the ability to orient oneself relative to a known environment) is a fundamental cognitive skill [6]. It is also a requirement in mobile robotics applications such as *teach-replay navigation*, where a robot is first led through a route by a guide (the teach step), and must later autonomously retrace the original path (the replay step) [1]. Visual teach-replay is subject to largely the same challenges faced by living organisms, i.e., the need to account for variations in visual stimuli within a

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given environment. Therefore, a case can be made for self-location Biologically Inspired Cognitive Architectures (BICA's).

The Difference Image Correspondence Hierarchy (DICH) is a cognitive architecture designed to enable self-location in mobile robots equipped with a single monocular camera. Other BICA's capable of self-location have been developed, but often in the context of simulated environments that are very simplified [3], or allow state data to be acquired directly instead of inferred from sensor inputs [4]; lack of clear ways to specify goals (e.g., setting destinations) is also a common limitation [3, 4]. In contrast, DICH has been developed from the beginning to operate in real-world robots and environments, relies exclusively on visual data, and implements a learning model accommodating of goal-directed training and operation.

DICH is a continuation of previous work on visual search [7] and mobile robot navigation [8]. The next section details the architecture's design and fundamentals, followed by experiments that demonstrate its effectiveness. The article closes with a discussion on the results achievement and directions for further research.

2 Architecture

The DICH architecture was designed to work with a mobile robot equipped with a single front-mounted camera, under the teach-replay navigation scenario. During the teach step, the robot collects a video record of the trip, which is stored to long-term memory; during the replay step, camera inputs are used along with teach step data to update two working memory modules (the "similarity map" and the "shift map"), from which estimates of the robot's location along the route, and possible drift from it, can be computed. The next subsections describe each of the architecture's components in detail.

2.1 *Difference Images*

Mammal vision requires continuous stimulus change to function properly: even when the exterior world is static, fixational eye movements ensure the images falling on our retinas never remain the same for long [5]. DICH seeks to capture this principle through the use of *difference images* as its basic percept. Let I_t be the instantaneous visual input at time t for a mobile robot as it advances towards a landscape. Assuming reasonable conditions (i.e. a minimally stable environment, smooth movement, etc.) I_t will vary gradually as the robot advances. Such changes can be quantified by computing the difference image J_t such that:

$$J_t = |I_t - I_{t-\delta}|, \quad \delta = \arg\min_{\delta > 0} \langle |I_t - I_{t-\delta}| \rangle \geq \tau \tag{1}$$

where the subtraction operator is defined for images as pixel-wise euclidean distance (so e.g. subtracting RGB pixels will result in a single scalar value), $\langle \cdot \rangle$ is the average operator and τ a system parameter.

Given an appropriate gap $\delta > 0$ and absent of saturation artifacts, difference images are largely invariant to ambient brightness, providing a degree of normalization across illumination conditions; moreover, the amount of change will vary depending on whether the robot is moving, which can be used as a self-motion cue. Finding that appropriate gap is not trivial, though: too short a gap will result in a mostly empty image, too large and it may become impossible to relate differences to actual scene elements. However, by constraining δ so that every J_t will average a difference at least τ, a degree of consistency across difference images can be achieved, even in the face of changes to physical parameters such as the robot's speed and direction of movement.

2.2 *Difference Image Pairing*

A difference image implicitly denotes a location along a route as the pair of viewpoints from which the raw images used to compute it were taken. Therefore, DICH uses difference image matching to perform self-localization over the length of a route—if current visual input matches a stored snapshot, the robot should be at roughly the same place.

When animals look at their surroundings, their eyes dart among a small set of *salient points* (e.g., corners or edges), which seem to provide enough information for effective visual recognition. This behavior is modeled by Image Processing Algorithms (IPA's) that select small patches called algorithmic Regions-Of-Interest (aROI's) from input images [9]. Image matching can be performed for aROI's in place of whole images.

DICH uses aROI's for difference image matching as follows. Let J_i be the *i*th teach difference image and J'_j the *j*th replay difference image. A list of salient point image coordinates $p_{j,k} = (u, v)$ are selected from J'_j as points of maximum difference within square patches of side $2\alpha + 1$. The patches themselves are extracted as corresponding aROI's $\rho_{j,k}$. Now if J_i and J'_j are spatially related, then for each $\rho_{j,k}$, there must be a region of J_i not far from coordinates $p_{j,k}$ that is similar to it. Therefore, for each salient point $p_{j,k}$, a *neighborhood* $\phi_{i,j,k}$ of side $2\beta + 1$ is extracted from J_i, and the similarity between J_i and J'_j is defined as the sum of similarities between each $(\rho_{j,k}, \phi_{i,j,k})$ pair:

$$\kappa_s(\mathrm{J}_i, \mathrm{J}'_j) = \sum_k \max_{x,y} \cos(\rho_{j,k}, \phi_{i,j,k}) \tag{2}$$

where:

$$\cos(\mathrm{A}, \mathrm{B}) = (\mathrm{A} * \mathrm{B}) \circ (\mathrm{A}^{\circ 2} * \mathbf{1}^{m_B \times n_B})^{\circ -\frac{1}{2}} \circ (\mathbf{1}^{m_A \times n_A} * \mathrm{B}^{\circ 2})^{\circ -\frac{1}{2}} \tag{3}$$

Is the *sliding cosine similarity* between $\mathrm{A}^{m_A \times n_A}$ and $\mathrm{B}^{m_B \times n_B}$, for $*$ the cross-correlation operator, $\circ$ and $^\circ$ respectively the Hadamard (i.e. element-wise) product and power operations [10], and $\mathbf{1}^{m \times n}$ a $m \times n$ matrix with all elements equal to 1. This is essentially a sliding version of the *cosine similarity* metric [2], where the cross-correlation between and computes the dot product for every translation of over, and the normalization factors are given by the other two formula terms. Figure 1a illustrates the process.

In animal self-localization, visual cues are combined with a sense of self-motion to produce reliable position estimates [6]. This is modeled in DICH by plotting all values of $\kappa_s(\mathrm{J}_i, \mathrm{J}'_j)$ over a range $(i_0, j_0) \leq (i, j) < (i_0 + h, j_0 + w)$ as a *similarity matrix*, and using linear regression to find a *trend* of high similarity values over it. This trend is represented by a line $l_j = (m_j, b_j)$.

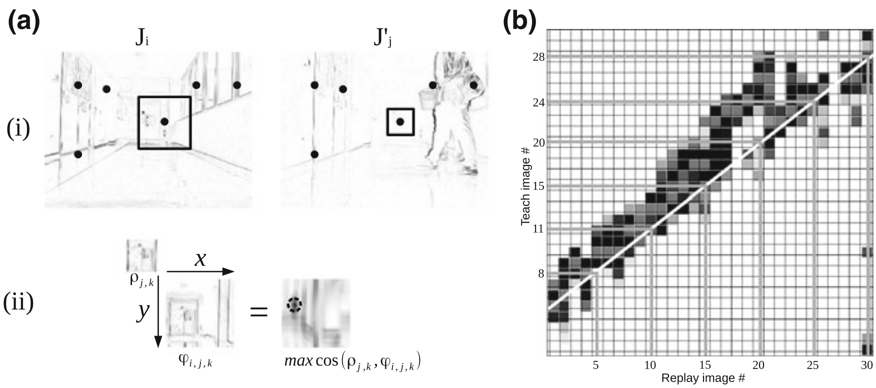

Fig. 1 Similarity map and trend computation. **a** Algorithmic regions-of-interest and neighborhoods are extracted at given salient points (*i*); sliding cosine similarity is computed for each (aROI, neighborhood) pair, and the maximum value (indicated here by the *dashed circle*) is taken as the similarity for that pair (*ii*). In this particular case, some salient points will produce weak responses, since they fell on an element not present in the teach difference image (a pedestrian who crossed in front of the robot during the teach step). However, this may still be compensated by the responses of the other points. **b** A similarity map represents at each cell the similarity between replay (horizontal axis) and teach (vertical axis) difference images. *Darker shades* of *gray* indicate higher similarity. The *white line* indicates the identified matching trend across the map. *Gray lines* indicate the estimated correspondence between replay and teach images

Difference image pairing can then be defined as:

$$g(\mathrm{J}'_j) = \mathrm{J}_i | i = m_j j + b_j \tag{4}$$

Figure 1b illustrates pairing function estimation from a similarity map.

2.3 Shift Estimation

Difference image pairing estimates how far the robot advanced along the teach route. The deviation from the original route can be inferred by computing the *shift* between teach and replay images—a length of horizontal sliding of one image over the other, such that features of both are "matched" as well as possible. Because scenes may change between teach and replay trips (due e.g. to the presence of moving elements), it's not effective to compare images wholesale. Instead, given a matched pair $(\mathrm{J}_i = g(\mathrm{J}'_j), \mathrm{J}'_j)$, *columns* of width γ are selected from teach image J_i one at a time for comparison to J'_j, and the resulting vectors summed into *shift vectors*:

$$\kappa_h(\mathrm{J}_i, \mathrm{J}'_j) = \sum_k \left(\mathbf{0}^n || \cos\left(\mathrm{J}_i\left[:, \gamma k : \gamma(k+1), \mathrm{J}'_j\right]\right)\right) \ll k \tag{5}$$

where $\|$ and $\ll$ are the vector concatenation and left shift operators, and $\mathbf{0}^n$ the zero vector of dimension n (for n equal to the width of J'_j). Padding and shifting of individual column similarity vectors is necessary to properly align results (e.g., $\cos\left(\mathrm{J}_i[:, 0 : \gamma], \mathrm{J}'_j\right)$) can only detect right shifts).

A shift vector describes shift likelihoods: the central value indicates the likelihood that no shift has taken place, while values prior to it represent the likelihood of a shift to the right, and values following, of a shift to the left. Concatenating successive shift vectors column-wise produces a *shift map*; see Fig. 2b for an example. A hill climbing algorithm can then be used to find a route of high likelihood across it, which will indicate whether, and to which side, the robot is drifting from the original route.

3 Experiments

A mobile robot equipped with a top-mounted camera was used to record a test session composed of two trips—a reference or *teach step* trip, and a comparison or *replay step* trip—in a corridor of about 20 m length. Teach and replay steps started

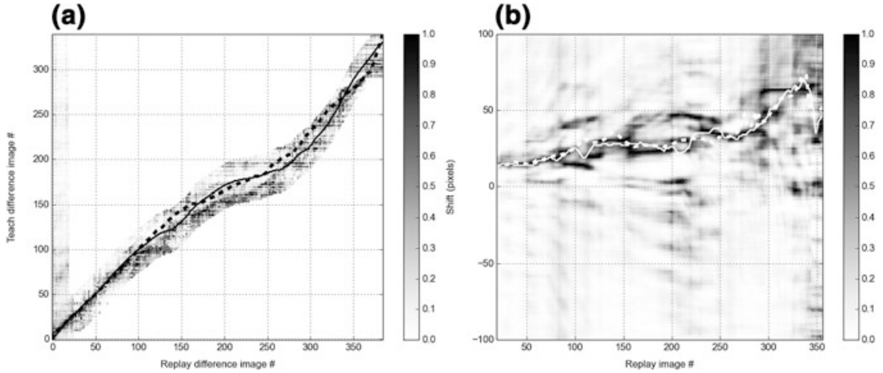

Fig. 2 Test session results, displayed as (composite) similarity (**a**) and shift (**b**) maps. *Darker shades* of *gray* indicate higher correspondence/shift likelihood. *Full lines* over the maps represent estimated image correspondences/shifts, and *dashed lines*, ground truth data. Horizontal axis is replay image index; vertical axis is teach image index for the similarity map, and shift in pixels for the shift map (with positive values indicating left shift, and negative values, right). The displayed similarity map is actually a composite of several computations between h teach and w replay difference images, combined in a manner consistent with image indexes

from the same position and advanced in the same direction, but in the teach step, after starting close to the left wall, the robot slowly drifted right until stopping close to the right wall; whereas in the replay step the robot remained close to the left wall for the duration of the trip. The corridor was empty during the teach step, but 30 s into the replay step three people come from behind the robot, staying on the right side of the field of view until walking away 20 s later.

A batch implementation of DICH was developed and applied to the video records offline. System parameters were set to $(\tau = 15, \alpha = 25, \beta = 49, \gamma = 16, w = 20, h = 50)$. In order to establish an initial location estimate over the whole route, the first similarity map is computed over the first w replay difference images and all teach difference images; after that, the estimate is iteratively updated by recomputing the similarity map for the h teach inputs closest to the latest pairing estimate and most recent w replay inputs. Ground truth data was computed manually by comparing the frames of teach and replay step video recordings.

As shown in Fig. 2, estimates and ground truth agree well in both similarity and shift maps; divergences arise occasionally, but always reverse later on. Both image pairing and shift estimation successfully coped with the variation in difference image change ratio, caused by the appearance of pedestrians in the replay step (this is the source of the slope change in the estimate curve in the middle of the similarity map). Results therefore indicate DICH was able to successfully estimate the robot's position along the route, as well as to identify sideways drift, in the image domain.

4 Conclusions

This article presented the Difference Image Correspondence Hierarchy (DICH), a biologically inspired cognitive architecture for enabling self-location in mobile robots. Experimental results show adequate performance under a range of input variations, suggesting there is merit in its premises. Currently the method's main weakness is the need to set parameters manually for optimal performance. However, research in the psychophysiology of vision may help determine reasonable defaults. The method's application in a robot navigation system (i.e. that would allow a mobile robot to drive itself) is also meant as a topic for future work.

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