

## Visualization of Signal Structure Showing Element Functioning in Complex Dynamic Systems – Cognitive Aspects

V.P. Mygal<sup>1,\*</sup>, G.V. Mygal<sup>1</sup>, L.M. Balabanova<sup>2</sup>

<sup>1</sup> N.E. Zhukovskiy National Aerospace University “Kharkiv Aviation Institute”,  
17, Chkalova St., 61070 Kharkiv, Ukraine

<sup>2</sup> National University of Civil Defense of Ukraine, 94, Chernyshevska St., 61023 Kharkiv, Ukraine

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The work is aimed at identifying the structure of the operation signals of the complex dynamic system elements. The structure reflects the space-time relationship of its components. The configuration of the primary structure and the nature of its restructuring contain cognitive information about the features of the functioning of the complex dynamic system elements. Parametric geometrization of signals of different nature was carried out in the space of dynamic events. This made it possible to transform a one-dimensional signal (response) into a closed trajectory of dynamic events, which serves as a geometric three-dimensional model of the functioning cycle. Its orthogonal projections are signatures whose configurations reflect the dynamic, energetic, and informational features of the natural decomposition of a signal into components. Therefore, their spatial distribution is integrally perceived in the form of a cognitive graphic image of a signal as a cycle. Its system analysis allows to: a) find changes in the cycle structure, comparing it with the previous one; b) determine the cycle type (stable, adaptive, evolutionary); c) assess the degree of its orderliness and balance; d) determine the nature of the configuration change under the influence of stress factors. On the one hand, visualization of the structure of different signals as information flows simplifies human-computer interaction. On the other hand, the analysis of packages of cognitive graphic images of electrophysiological signals of a person allows to: a) identify and take into account when training his psychophysiological features; b) assess his adaptive capacity; c) identify stress and manifestation of psychological dissonance. In general, the cognitive visualization of different signals as information flows will contribute to the development of intuition in the process of training the operator, as well as improving its effectiveness.

**Keywords:** Complex dynamic systems, Signal geometrization, Visualization, Cognitive graphics, Signal structure, Signatures, Cognitive graphic images.

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### 1. INTRODUCTION

A topical issue of man-machine interaction is ambiguous perception of information flows from various sensors (biosensors, sensors, etc.). Increase of their number in complex dynamic systems (CDS) gave rise to the search of new signal processing methods. Consequently, there are numerous means of their visualization. All this affects operational safety under unpredictable conditions. It also turned out that the usual graphic images of signals cause the operator (expert) to associate with the characteristics studied. This is the reason why cognitive graphics means do not allow to avoid ambiguity when analyzing various signals. It has been also established that perception of the variety of graphic images depends on the features of the psychophysiological state of the human. It is caused by interaction of subsystems of his/her body with external and internal stress-factors. Due to the simultaneous occurrence of physiological and mental processes (self-regulation, adaptation, cognitive representation, etc.), a subjective perception of an unpredictable situation arises. The effect of human cognitive and analytical capabilities on the efficiency of man-machine interaction is constantly rising.

The use of known methods of computer graphics for the analysis of the large body of ill-defined data does little to the achievement of the required “cognitive”

effect, acquiring new knowledge. The reason is in difficulties to get graphic images not invoking direct subject associations in decision makers. The key issue is thus to select a form of graphic image allowing the required “cognitive effect” to arise. Therefore, the same visual cognitive graphics means in terms of form of representation are required. They will be convenient for the perceptual unity and development of intuition at training. The visualization form will exclude ambiguity in interpretation of the information received and stimulate mental activity. It is possible if sensor and biosensor signals various in nature are considered as natural information flows. In this case, their hidden structure can be analyzed in the same space, since of the management structure in the animate and inanimate nature is similar [1]. It is also indicated by the analogy between image recognition processes in cognitive processes and dynamic processes of natural system form generation [2]. Thus, interdisciplinary means are needed to visualize the structure of information processes.

**Objective of this paper** is to identify cognitive information in the hidden structure of signals of the CDS elements.

### 2. GEOMETRIZATION OF COMPLEX SIGNALS

The use of cognitive and analytical capabilities of the human requires an interdisciplinary approach to

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\* [valeriy.mygal@gmail.com](mailto:valeriy.mygal@gmail.com)

visualize the complex signals of various nature. It is based on the geometrization of the dynamic structure of any signal. For that purpose we will use the extreme differential principle of the minimum length or Hertz curvature. The extreme Lagrange principle, Hamilton principle and Jacoby principle are derived therefrom [3]. The interrelation of extremal variational principles and the Le Chatelier-Braun thermodynamic principle allows, on their basis, to transform the generalized phase space (state - speed - time) into parametric space (state - speed - acceleration). For that purpose, we will apply such principles to small changes of state  $X$ , and to the speed of its change  $dX/dt$  and acceleration  $d^2X/dt^2$ . Their multiplication reflects the probability of a dynamic event, which can be displayed as a point in the space of dynamic events [4]. Therefore, derivatives of a one-dimensional time signal (response, characteristics, etc.) of sensor or biosensor allow turning it into three interrelated time dependences  $X(t)$ ,  $dX(t)/dt$  and  $d^2X(t)/dt^2$ . The representation of these dependences in parametric space (state - speed - acceleration) turns any response of sensor or biosensor into a closed trajectory of dynamic events. With such a geometrization, the causal connection between events is displayed in the form of a 3D trajectory (see Fig. 1b and Fig. 2b). In this case, any hidden features of the dynamics of one-dimensional signals convert into static ones. Therefore, the trajectory of dynamic events can serve as a 3D-model of signal. Such a model is a geometric illustration of the Hertz principle. Consequently, its perception may have a “cognitive effect”. Really, those orthogonal projections of the 3D-model of animated and inanimate nature objects are parametric signatures of the 1<sup>st</sup> and 2<sup>nd</sup> order signal [4, 5]. Configurations of such signatures are formed by geometrically ordered sections differing by length, slope and curvature. Physically, such sections differ by linear density of dynamic events and spatiotemporal distribution (Fig. 1, Fig. 2). Signature configurations are perceived as a kind of cognitive cycles, in which extreme principles of mechanics are reflected. Areas of the 1<sup>st</sup> and 2<sup>nd</sup> order signatures have dimensions of action, energy and power. Consequently, such signatures of the information flow reflect the dynamic, energetic and information cycles. Configuration of the signature  $X(t) - dX(t)/dt$  is thus perceived as a sequence of dynamic states. In essence, it is the phase portrait. Configuration of the signature  $X(t) - d^2X(t)/dt^2$  reflects the spatio-temporal distribution of energy in counterphase components of the signal. The nature of interaction of dynamic variables visualizes the configuration of the signature  $dX(t)/dt - d^2X(t)/dt^2$ . It is cognitively perceived as an information functioning cycle with the power proportional to its area.

Hence, interrelation of the 3D model and configuration of three signatures allows to analyze information sources of the CDS elements from complementary points of view. In particular, it is evidenced by the systemic analysis of signatures of the temporal and spectral photoresponses of semiconductor sensors (photoelectric receivers, detectors, spectrometers). It has been established that the “cognitive effect” is present in: a) the spatiotemporal decomposition of information flow signature

configuration into component sections; b) area covered with signatures and pattern of its distribution over quadrants; c) interrelation of parameters of the geometrically ordered components. The following are also information bearing: a) partial contributions of the components of  $P_i$ , which are proportional to the product of their length, slope or curvature; b) the number of counterphase components of the signature configuration. Moreover, the area covered by the  $X(t) - dX(t)/dt$  signature configuration may be viewed as the power of the subset of microstates  $W$ . Natural logarithm  $W$  is proportional to entropy  $H$  which is a universal measure of distribution order  $W$  [6]. Energy balance of counterphase processes may be assessed by the ratio of areas of the first and fourth quadrants of the signature  $X(t) - d^2X(t)/dt^2$ . It has been established that this ratio is rather sensitive to structural defects of semiconductor sensors [5].

### 3. PACKETS OF SIGNAL SIGNATURES AS COGNITIVE GRAPHIC IMAGES

Configuration of signatures  $dX(t)/dt - d^2X(t)/dt^2$  of self-organized elements (functional characteristics of smart materials, sensors, biosensors etc.) and their packets have a considerable “cognitive effect”. E.g., comparison of signatures of sensors and biosensors (temporal and spectral response, dynamic Volt-ampere characteristics, etc.) showed that their configurations are dynamically similar and have the highest information bearing effect [4].

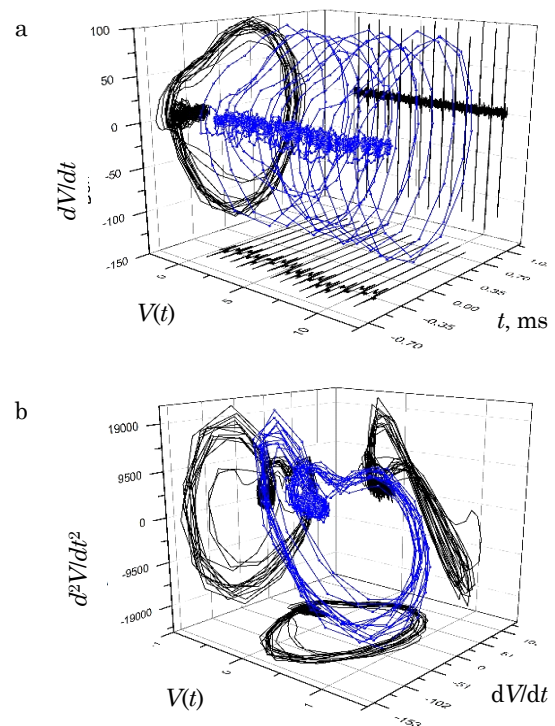


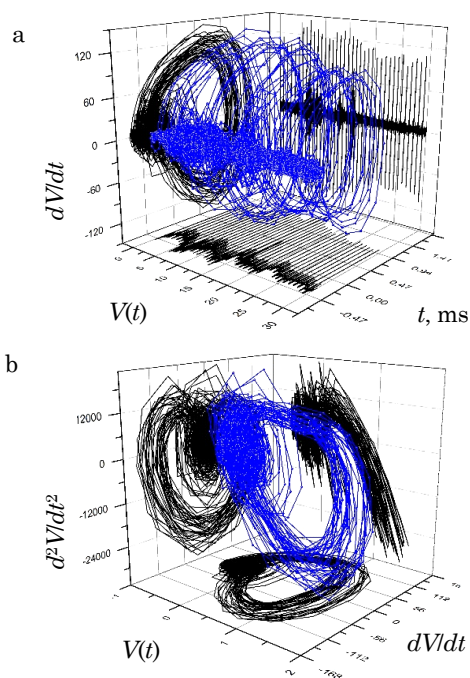
Fig. 1 – Signature packets of human ECG in normal condition

First, the configuration reflects the structure of the information cycle of functioning of the CDS elements. Second, the signature area allows to visually assess its strength and order. Third, the cycle efficiency can be

analyzed based on the ratio of the areas of the signature quadrants. Thus, the ratios of these areas are indicators of the balance of power  $B_{ij}$  between the main phases of the cycle. The totality of  $B_{ij}$  values as a matrix allows to analyze efficiency of the functioning cycle.

In this way characteristic signs of the signature configuration systemically reflect the features of the structure of information cycles of functioning of various CDS elements. Hence, cognitive perception of signals of different nature may be complemented by statistical analysis of the dynamic, energetic and informational features of their structure. Identical algorithms to visualize the signal structure allow to make functioning cycles of various CDS elements consistent. This and estimation of entropy, order and balance of the cycle convert 3D model and signatures of information flows into cognitive graphic images (CGI).

Individuality of the transient psychophysiological state of the human under the influence of stressors is hidden in spatiotemporal features of dynamics of electro-physiological signals (ECG, EEG, EOG and others) [7-9]. However, in the event of their parametric geometrization, information arrays are naturally structured. As can be seen from comparison of Fig. 1b and Fig. 2b, it is the electrocardiogram (ECG) signature configuration that makes the characteristic cognitive signs evident.



**Fig. 2** – ECG and packets of the ECG-signatures of the same person under information stress

And the nature of CGI changes under stressor influence shows rearrangement of the feedback loop. That is why signature packets of electrophysiological signals are the most information-bearing to determine the psychophysiological state of the human. The nature of rearrangement of the signature configuration can be compared with previous packets available in the knowledge base. It offers the possibility to determine the psychophysiological state of the human in real time.

In particular, the cognitive information may include: a) cycle rearrangement nature (gradual, discrete); b) trajectories density and the nature of its changes in the cycle (uniform, non-uniform); c) existence of stable cycles (attractors) and their number; d) the presence of fluctuations (disturbances) and the nature of their distribution over the cycle. With their aid, it is possible to determine the psychophysiological level and reserves, and adaptation level, tension index within 10 to 30 seconds. It should be noted that the same parameters can be determined on the basis of cardiac rhythm variability after 300 to 500 seconds.

As can be seen from comparison of Fig. 1 and Fig. 2, the influence of external and internal stress factors on the structure of the human cardiovascular system functioning cycle is manifested. The nature of rearrangement of the cycle can be assessed by using various entropies (Boltzmann, Kolmogorov, etc.). Therefore, when analyzing the cycle of operation, one can apply the fundamental thermodynamic criteria of stability, balance, reversibility. It should be noted that the results of concomitant studies of CGI of electrophysiological signals and psychological tests (Cogan, Luscher, etc.) are not contradictory. It can be suggested that there is a link between CGI features of electroencephalogram and individual cognitive style.

#### 4. CONCLUSIONS

Based on the extreme principles of mechanics, the means of signal processing, display and analysis have been unified. Geometrization of signals of various nature allowed to identify: a) their natural decomposition into the dynamic, energetic and information components; b) power imbalance between the main phases of the functioning cycle; c) influence of stressors on the nature of rearrangement of the electrophysiological signal structure. At the same time, a holistic perception of the structure of the signal functioning as a CGI provides qualitatively new possibilities. More specifically: a) identification of cycle structure changes by comparing it with previous cycles; b) analysis of the CGI configuration rearrangement nature under the influence of stress factors; c) determination of the functioning cycle type (stable, adaptive, evolutionary), and evaluation of its complexity, order and balance. Consequently, the configurations of signal signatures are characterized by a set of cognitive characteristic features. Moreover, principles of system dynamics and criteria of statistical thermodynamics can be used when analyzing CGI signature configurations.

Spatiotemporal order of signature configuration components proves the idea of N. Viner that the most common form of signal organization is its linear invariant. Further articulation of the configuration concept and information flow structure allows to move from the linear invariant to the concept of mutual order of two sets. Such principle of mutual order is prescribed by the concept of spatiotemporal isomorphism. It is implemented in the signal signature configuration and turns them into a code. It should be noted that the structure of mental codes can be also described in terms of spatiotemporal isomorphism. It is confirmed by the similarity of characteristic signs in signatures of various

electrophysiological signals. Signatures of the 1<sup>st</sup> and 2<sup>nd</sup> order of other self-organized objects are therefore important. They are natural CGIs whose classification would simplify the man-machine interaction. The use of natural CGIs also activates a person's visual (right-handed) abstract thinking when learning. In summary, identification of the psycho-physiological state of the human by using CGIs increases the use of visual thinking.

Cognitive similarity of characteristic signs of information flows of various nature stimulates thinking in more common forms. And the use of intuition contributes to the acquisition of new knowledge. In fact, we prove by using logics and discover due to intuition.

Intuition is based on the recognition of a symbol or a graphic image of an object. In summary, identification of the psychophysiological state of the human by using CGI increases the use of visual thinking.

It should be noted that CGI signature packets of electrophysiological signals of the human allow to: a) identify his/her psychophysiological features; b) evaluate his/her adaptation possibilities; c) identify stress and seeds of dissonance in organism functioning. Moreover, cognitive visualization of information flows of various nature contributes to the development of intuition when training an operator and to the increase of his efficiency. All this allows to increase the safety of CDS functioning.

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## Візуалізація структури сигналів функціонування елементів складних динамічних систем – когнітивні аспекти

В.П. Мигаль<sup>1</sup>, Г.В. Мигаль<sup>1</sup>, Л.М. Балабанова<sup>2</sup>

<sup>1</sup> Національний аерокосмічний університет ім. М.С. Жуковського «Харківський авіаційний інститут», вул. Чкалова, 17, 61070 Харків, Україна

<sup>2</sup> Національний університет цивільного захисту України, вул. Чернишевська, 94, 61023 Харків, Україна

Робота спрямована на виявлення структури сигналів функціонування елементів складних динамічних систем. Структура відображає просторово-часові взаємозв'язки її складових. Конфігурація первинної структури та характер її перебудови містить когнітивну інформацію про особливості функціонування елемента складної динамічної системи. Параметрична геометризація сигналів різної природи проводилася в просторі динамічних подій. Це дозволило перетворити одновимірний сигнал (відгук) в замкнуту траєкторію динамічних подій, яка служить геометричною 3D-моделлю циклу функціонування. Його ортогональні проєкції є сигнатурами, конфігурації яких відображають динамічні, енергетичні та інформаційні особливості природної декомпозиції сигналу на складові. Тому їх просторовий розподіл цілісно сприймається у вигляді когнітивного графічного образу сигналу як циклу. Його системний аналіз дозволяє: а) знайти зміни в структурі циклу, порівнюючи його з попереднім; б) визначити тип циклу (стабільний, адаптивний, еволюційний); в) оцінити ступінь його впорядкованості і збалансованості; г) визначити характер перебудови конфігурації під впливом стрес- факторів. З одного боку, візуалізація структури різних сигналів як інформаційних потоків спрощує взаємодію людини з комп'ютером. З іншого боку, аналіз пакетів когнітивних графічних образів електрофізіологічних сигналів людини дозволяє: а) виявити і врахувати при навчанні його психофізіологічні особливості; б) оцінити його адаптивну здатність; в) виявити стрес і прояв психологічного дисонансу. Загалом, когнітивна візуалізація різних сигналів як інформаційних потоків сприятиме розвитку інтуїції в процесі навчання оператора, а також підвищенню його ефективності.

**Ключові слова:** Складні динамічні системи, Геометризація сигналів, Візуалізація, Когнітивна графіка, Структура сигналів, Сигнатури, Когнітивні графічні образи.