Conceptual-visual metalanguage of hybrid intelligent systems

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Abstract. The urgency of the metalanguage is caused by the development of visually-shaped representations and reasoning in hybrid and synergetic intelligent systems. The absence of formalisms determines the high science intensity of special environments for manipulating and processing visual models. The formalization of the metalanguage is a condition for the development of hybrid intelligent systems with a heterogeneous visual field; it ensures cooperation, relativity, the complementarity of collective natural and artificial intelligence capable of visual thinking and speaking in verbal-symbolic languages.

1. Introduction

The long experience of the Kaliningrad school of hybrid artificial intelligence confirms not only the advantages of functional hybrid intelligence systems (FHIS), but also contrasts their shortcomings, for example, interaction with users and specialists only through symbolic-logical methods of representing information that practically does not activate the visually-shaped, right hemisphere reasoning of the decision-maker (DM). Visualization and, in particular, schematization provides understanding and explanation of problems and their solutions by FHIS, activates the mechanisms of intuitive, insightful thinking, which is especially important in the context of diversity of opinions. Visualization of complex structure and dynamics of changing problem situations, the principle of "seeing the problem at a glance" will allow to act promptly.

Visually-shaped representations and cognitive modeling were considered in papers by D.A. Pospelov, A.A. Zenkin, G.P. Shchedrovitsky, Yu.R. Val'kman, B.A. Kobrinsky, O.P. Kuznetsov, G.S. Osipov, V.B. Tarasov, I.B. Fominykh, T.A. Gavrilova, A.E. Yankovskaya, etc. Visual languages are developed for functional programming, programming by examples, finite automata, data flows and other domains [1]. The implementation of these languages requires considerable effort, development in each case of special environments for creation, manipulation and processing of visual models. To reduce them, the formalized model of visual language based on the principles of system theory and system analysis is proposed. It should be considered within scope of I.B. Fominykh's opinion: "Solving problems of representation of right hemispheric mechanisms by left hemispheric means, research and modeling of the interaction of figurative and symbolic-logical thinking, the forming methods of figurative thinking computer support are of considerable interest".

2. Modeling of visually-shaped representations as semiotic system

The concept of the semiotic system D.A. Pospelov, G.S. Osipov [2] is applied for modeling of reasoning on visually-shaped schematic images [2 - 6]:

$$vl = < VT, VS, VA, VP, \upsilon\tau, \upsilon\sigma, \upsilon\alpha, \upsilon\pi >, \quad (1)$$

where VT, VS, VA are sets of basic symbols, syntactic rules and axiom-knowledge about the subject domain (semantic rules) respectively; VP is a set of rules for inference of solutions (pragmatic rules); $\upsilon\tau$, $\upsilon\sigma$, $\upsilon\alpha$, $\upsilon\pi$ are sets of rules for changing sets VT, VS, VA, VP respectively. The sets $VT, VS, VA, VP, \upsilon\tau, \upsilon\sigma, \upsilon\alpha, \upsilon\pi$ in equation (1) are defined by the expressions:

$$VT = \langle P, D, VR \rangle,$$

$$VS = \langle VT, VN, PRU \rangle,$$

$$VA = \langle DO, G^{\mathrm{RES}}, G^{\mathrm{ACT}}, G^{\mathrm{PR}}, G^{\mathrm{R}} \rangle,$$

$$DO = \langle RES, ACT, PR, R \rangle,\ G^{\mathrm{RES}} : RES \to P,\ G^{\mathrm{ACT}} : ACT \to P,\ G^{\mathrm{PR}} : PR \to D,\ G^{\mathrm{R}} : R \to VR,$$

$$VP = \{\langle AG, act, M, W \rangle\},$$

$$\upsilon\tau = \langle \Delta P, \Delta D, \Delta VR \rangle,$$

$$\upsilon\sigma = \langle \upsilon\tau, \Delta VN, \Delta PRU \rangle,$$

$$\upsilon\alpha = \langle \Delta DO, G^{\Delta\mathrm{RES}}, G^{\Delta\mathrm{PR}}, G^{\Delta\mathrm{R}} \rangle,$$

$$\Delta DO = \langle \Delta RES, \Delta ACT, \Delta PR, \Delta R \rangle,$$

$$G^{\Delta\mathrm{RES}} : \Delta RES \to \Delta P,\ G^{\Delta\mathrm{CT}} : \Delta ACT \to \Delta P,\ G^{\Delta\mathrm{PR}} : \Delta PR \to \Delta D,\ G^{\Delta\mathrm{R}} : \Delta R \to \Delta VR,$$

$$\upsilon\pi = \{\langle \Delta AG, \Delta act, \Delta M, \Delta W \rangle\},$$

where, in addition to the previously introduced notation P is a set of visual primitives; D is a set of visual dimensions characterizing visual primitives; VR is a set of visual relations between one or more primitives [4]; VN is a dictionary of nonterminal symbols; PRU is a set of production rules; RES, ACT, PR, R are sets of concepts of resources, actions, properties and relations, respectively; AG is a set of models of native speakers (experts, elements, agents), to which the behavior norm is addressed (various social prohibitions and restrictions imposed by the community on a separate speaker); $act \in ACT$ is the action, defined on the set of actions ACT, the object of normative regulation (the content of the norm); M is a set of systems of modalities associated with the action, for example, the system of norms expressed by deontic modalities: $M_N = \{ma, al, in, proh\}$, where ma is "mandatory", al is "allowed", in is "indifferent", $proh$ is "prohibited"; W is a set of models of worlds in which the norm is applicable (the conditions of application, the circumstances in which the action should or should not be performed) [7]; ΔP, ΔD, ΔVR, ΔVN, ΔPRU, ΔRES, ΔACT, ΔPR, ΔR, ΔAG, ΔM, ΔW are the sets of admissible changes of the sets P, D VR, VN, PRU, RES, ACT, PR, R, AG, M, W respectively; Δact is a set of permissible changes in the content of the norm act.

As shown in [8], the languages of professional activity are poly-languages [9]. This is due to the inherent structure of the external world and the specificity of the asymmetry of verbal-sign and visually-shaped representations of resources, properties, actions, structures, situations, states, the behavior of the control object and, taking into account the subject of management activities, of goals, tasks, plans, and assessments. In this paper, visually-shaped representations are considered as a multilayered hierarchy of semiotic systems.

3. The multilayered model of conceptual-visual metalanguage of visually-shaped representations

In [9] the family of verbal-symbolic languages for description of resources, operations, structures, situations, states, behavior of the control object, as well as goals, plans and problems is represented. In [10] eight levels of visual languages are allocated for the implementation of automated reasoning in intelligent systems: 1) conceptual and visual basis vl^1; 2) resources, actions and properties vl^2; 3) hierarchies of resources, actions and properties vl^3; 4) spatial and production structures vl^4; 5) states, situations and events vl^5; 6) tasks and problems vl^6; 7) experts' reasoning models vl^7; 8) integrated models of collective intelligence reasoning vl^8. In this case, the developer has a set of components for constructing conceptual-visual metalanguage, describing the complex problem solving by combining several interrelated processes of reasoning in different languages. Depending on the requirements of the problem some levels could be missed. Thus, the conceptual-visual metalanguage can be formally represented by the expression:

$$mvl = < vl^1, vl^2, vl^3, vl^4, vl^5, vl^6, vl^7, vl^8, VLR >,$$

where VLR is a set of relations between language elements vl^k, $k \in \Gamma$, $k \in [1,\ 8]$.

The metalanguage is visualized by the "layered pie" (Figure 1) of semiotic systems in which the image signs (below the images) reflect reality at two image reflection levels of three distinguished in [11]: the level of representations (secondary images of objects) and verbal-logical (symbolic-logical) thinking. At the bottom of the "layered pie" are dictionaries of concepts and relations, a conceptual-visual basis on which the family of descriptive languages arranged in levels is built.

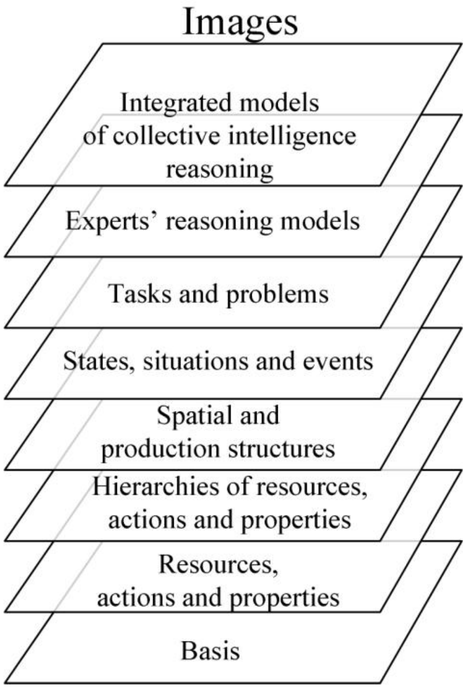


Figure 1. The multilayered metalanguage model.

Each layer of image representation (Figure 1) is associated with a semiotic system containing: 1) the core of the base signs (terminal alphabet) VT^k; 2) derived signs VN^k, formed according to the rules PRU^k. The visual core of the higher layer languages can contain the signs of the core of the lower layer $VT^k \subseteq VT^{k+1}$ and signs formed outside the core of the lower layer language $VT^{k+1} \cap VN^k \neq \varnothing$, $k \in \Gamma$, $k \in [1,\ 7]$.

Let's consider interrelations of the images formed by syntactic rules, at various layers of metalanguage.

The conceptual-visual basis of the language is in the first layer. It's a set of basic concepts and forms needed to build images on higher layers.

The first layer language vl^1 uses heuristic rules PRU^1 for constructing of images of derivative (composite) relations $vr^1 \in VR^1 \subseteq VT^1$ from P^1, D^1 and VR^1:

$$vl^1(P^1, D^1, VR^1, PRU^1) = \{vr^1\}.$$

At the second layer language vl^2, heuristics PRU^2 are used to generate images of resources $res^2 \in RES^2 \subseteq VT^2$, actions $act^2 \in ACT^2 \subseteq VT^2$ and properties $pr^2 \in PR^2 \subseteq VT^2$ without regard for their hierarchy using the definition relations $VR_1^1 \subseteq VR^1$:

$$vl^2(P^1, D^1, VR_1^1, PRU^2) = RES^2 \cup PR^2 \cup ACT^2.$$

At the third layer, inclusion relations $VR_5^1 \subseteq VR^1$ and heuristics PRU^3 formalize the hierarchies of resources $res^3 \in RES^3 \subseteq VT^3$, actions $act^3 \in ACT^3 \subseteq VT^3$ and properties $pr^3 \in PR^3 \subseteq VT^3$:

$$vl^3(P^1, D^1, RES^2, PR^2, ACT^2, VR_5^1, PRU^3) = RES^3 \cup PR^3 \cup ACT^3.$$

The fourth layer formalizes the spatial $str_1^4 \in STR_1^4 \subseteq VT^4$, operational and technological $str_3^4 \in STR_3^4 \subseteq VT^4$ structures on the basis of images defined at previous layers using temporal $VR_3^1 \subseteq VR^1$, spatial $VR_4^1 \subseteq VR^1$ and cause-effect $VR_6^1 \subseteq VR^1$ relations, as well as heuristics PRU^4:

$$vl^4(P^1, D^1, RES^3, PR^3, ACT^3, VR_3^1, VR_4^1, VR_6^1, PRU^4) = STR_1^4 \cup STR_3^4.$$

At the fifth layer heuristics PRU^5 formalize images of situations $sit^5 \in SIT^5 \subseteq VT^5$ and signs of states $st^5 \in ST^5 \subseteq VT^5$:

$$vl^5(STR_1^4, STR_3^4, PRU^5) = SIT^5 \cup ST^5.$$

At the sixth layer, images of homogeneous $prb^{\mathrm{h}\,6} \in PRB^{\mathrm{h}\,6} \subseteq VT^6$ and heterogeneous $prb^{\mathrm{u}\,6} \in PRB^{\mathrm{u}\,6} \subseteq VT^6$ problems are specified on the basis of image images of the previous layers and heuristics PRU^6:

$$vl^6(P^1, D^1, RES^3, PR^3, ACT^3, VR^1, ST^5, PRU^6) = PRB^{\mathrm{h}\,6} \cup PRB^{\mathrm{u}\,6}.$$

At the seventh layer, heuristics PRU^7 form images of autonomous methods $met^{\mathrm{a}\,7} \in MET^{a\,7} \subseteq VT^7$ for solving problems simulating the expert's reasoning:

$$vl^7(P^1, D^1, RES^3, PR^3, ACT^3, VR^1, PRU^7) = MET^{\mathrm{a}\,7}.$$

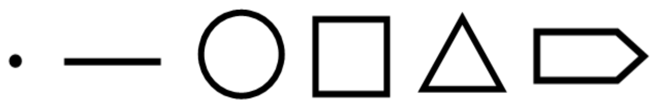
At the eighth layer, integrated methods $met^{\mathrm{u}\,8} \in MET^{\mathrm{u}\,8} \subseteq VT^8$ for solving problems simulating the reasoning of the team of experts are specified, based on images of the previous layers and heuristics PRU^8:

$$vl^8(P^1, D^1, RES^3, PR^3, ACT^3, VR^1, ST^5, SIT^5, PRB^{\mathrm{h}\,6}, PRB^{\mathrm{u}\,6}, MET^{\mathrm{a}\,7}, PRU^8) = MET^{\mathrm{u}\,8}.$$

Such multi-layer model of conceptual-visual language is a tool for a complex description of the domain of various degrees of generalization, which forms it from a set of simpler models. As an example, let us consider the use of this model for describing the alphabet of the first two layers of the metalanguage for the FHIS of the operational and dispatching regional power systems management.

4. Basic layers of conceptual-visual metalanguage

Analysis of papers on visual control, cognitive graphics, methods of information visualization [3, 6, 10] made it possible to identify the main figures underlying the conceptual-visual metalanguage (Figure 2a), and the set of pictograms [12], examples of which are shown in Figure 2b, for constructing schematized images of resources, properties and actions in the management of the power system.



(a)

(b)

Figure 2. Basic shapes vocabulary of the language of the FHIS for visual control: (a) basic shapes of visual metalanguage; (b) examples of pictograms for constructing images of resources, properties and actions.

A point is the basis of measurements; it generates a line, a movement. A straight line is the component of all geometric figures. The circle is a universal symbol of integrity, continuity and initial perfection. The square symbolizes thing or resource category [12], the triangle symbolizes property category and the arrow symbolizes action category. These forms in combination with the plane, color, texture, the set of pictograms that represent the visual "names" of concepts, as well as syntactic rules for recording visual role relationships VR are enough for constructing of a schematic image of any complexity.

At the first layer vl^1 of the metalanguage the derivative primitives, dimensions and relations are constructed with heuristic rules PRU^1 from the kernel's graphic primitives. As can be seen from Figure 2a limited, relatively small set of graphic primitives is required to represent the basic elements of the visual meta-language of power system management: straight line segment, circle, pictogram and filling (Figure 3). These primitives in turn can be described by the set of points that make up them. The relation of the definition vr_1^1 is represented graphically by a rectangle divided into two parts: the top contains the primitive to be defined, and the lower one contains definition. Formally this relation is written with the sign "=".

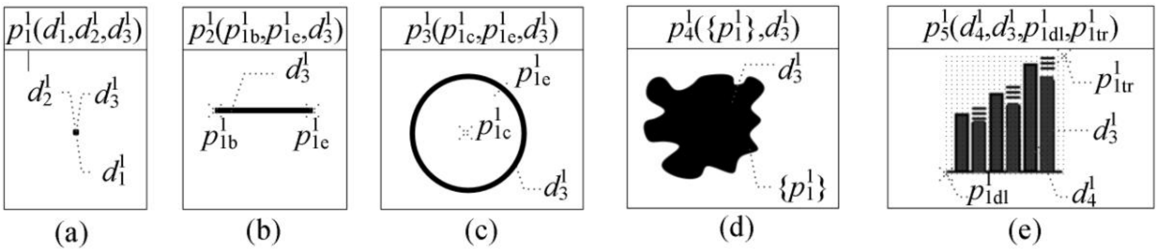


Figure 3. Graphical primitives of the first layer language: (a) point; (b) straight line segment; (c) circle; (d) filling; (e) pictogram.

The point in this paper is understood as a square with the size of one pixel with coordinates on the plane and color. For images drawn by hand fuzzy points and the methods of fuzzy geometry should be used. The primitive "point" p_1^1 has visual dimensions: the coordinates on the plane $d_1^1 \in [0, d_{1\max}^1]$, $d_2^1 \in [0, d_{2\max}^1]$ (Figure 4a), where, $d_{1\max}^1$, $d_{2\max}^1$ are the maximum values of the coordinates; the color $d_3^1 \in [0,100]$ on the scale "Grayscale" (Figure 4b). The point is displayed according to the rule:

$$p_1^1(d_1^1, d_2^1, d_3^1) = pru_1^1(d_1^1, d_2^1, d_3^1). \tag{2}$$

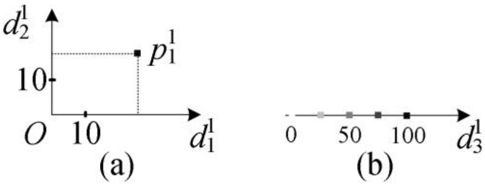


Figure 4. Visual measurements of the graphic primitive "point": (a) the coordinates of the point on the plane; (b) the color of the point.

When describing graphic primitives in this paper, the coordinates d_1^1 and d_2^1 are given in the local coordinate system of the primitive. When constructing a schematic image, the local coordinates of the primitive are recalculated into the image coordinate system, and primitive rotation and scaling can be performed. These operations are not considered in the present paper because of the absence of semantic load.

According to the rule (2) of generating the visual primitive "point" p_1^1, the primitive "line segment" can defined:

$$p_2^1(p_{1b}^1, p_{1e}^1, d_3^1) = \Big\{ p_1^1(d_1^1, d_2^1, d_3^1) \,|\, d_2^1 = \lfloor (d_1^1 - d_{1b}^1)(d_{2e}^1 - d_{2b}^1)(d_{1e}^1 - d_{1b}^1)^{-1} + d_{2b}^1 \rceil, d_{1b}^1 = d_1^1(p_{1b}^1),$$
$$d_{2b}^1 = d_2^1(p_{1b}^1),\ d_{1e}^1 = d_1^1(p_{1e}^1),\ d_{2e}^1 = d_2^1(p_{1e}^1),\ d_1^1 \in [d_{1b}^1, d_{1e}^1],\ d_2^1 \in [d_{2b}^1, d_{2e}^1], d_1^1, d_2^1 \in \mathbb{Z} \Big\},$$

where $\lfloor x \rceil$ is the rounding operation of the number *x* to the nearest integer.

The primitive “circle” is defined by the expression:

$$p_3^1(p_{1c}^1, p_{1e}^1, d_3^1) = \Big\{ p_1^1(\lfloor d_1^1 \rceil, \lfloor d_2^1 \rceil, d_3^1) \,|\, (d_1^1 - d_{1c}^1)^2 + (d_2^1 - d_{2c}^1)^2 = (d_{1e}^1 - d_{1c}^1)^2 + (d_{2e}^1 - d_{2c}^1)^2$$
$$d_{1c}^1 = d_1^1(p_{1c}^1),\ d_{2c}^1 = d_2^1(p_{1c}^1),\ d_{1e}^1 = d_1^1(p_{1e}^1),\ d_{2e}^1 = d_2^1(p_{1e}^1) \Big\}.$$

The fill is described by the expression:

$$p_4^1(\{p_1^1\},d_3^1)=\Big\{p_1^1(d_1^1,d_2^1,d_3^1)\,|\,\exists p_{1\mathrm{h}}^1\exists p_{1\mathrm{l}}^1(d_{1\mathrm{l}}^1,, d_1^1,, d_{1\mathrm{h}}^1)\wedge\exists p_{1\mathrm{h}}^1\exists p_{1\mathrm{l}}^1(d_{2\mathrm{l}}^1,, d_2^1,, d_{2\mathrm{h}}^1),$$

$$p_{1\mathrm{h}}^1, p_{1\mathrm{l}}^1\in\{p_1^1\},\ d_{1\mathrm{h}}^1=d_1^1(p_{1\mathrm{h}}^1),\ d_{2\mathrm{h}}^1=d_2^1(p_{1\mathrm{h}}^1),\ d_{1\mathrm{l}}^1=d_1^1(p_{1\mathrm{l}}^1),\ d_{2\mathrm{l}}^1=d_2^1(p_{1\mathrm{l}}^1),\ d_1^1,d_2^1\in\breve{y}\Big\}.$$

Graphical representation of the pictogram is a set of points corresponding to its raster image; it’s generated by the rule pru_2:

$$p_5^1(d_4^1,d_3^1,p_{1\mathrm{dl}}^1,p_{1\mathrm{tr}}^1)=\{p_1^1(d_1^1,d_2^1,d_3^1)\,|\,p_1^1(d_1^1,d_2^1,d_3^1)\in pru_2^1(d_4^1,d_3^1,p_{1\mathrm{dl}}^1,p_{1\mathrm{tr}}^1)\},$$

where d_4^1 is the bitmap image of the pictogram , d_3^1 is its color, $p_{1\mathrm{dl}}^1$, $p_{1\mathrm{tr}}^1$ are the lower left and the upper right points.

At the second layer of the metalanguage images of resources, actions, properties and relationships are formed from the visual primitives of the first layer (Figure 4).

The graphical representation of the concept of "resource" $res^2\in RES^2$ (Figure 4a) can be formally represented by the expressions:

$$res^2(p_{1\mathrm{dl}}^1,p_{1\mathrm{tr}}^1,d_3^1)=r_1^{2\mathrm{res\ pr}}(res^2,p_{1\mathrm{dl}}^1)\circ r_1^{2\mathrm{res\ pr}}(res^2,p_{1\mathrm{tr}}^1)\circ r_1^{2\mathrm{res\ pr}}(res^2,d_3^1)=$$

$$=p_2^1(p_{1\mathrm{dl}}^1,p_{1\mathrm{dr}}^1,d_3^1)\cup p_2^1(p_{1\mathrm{dr}}^1,p_{1\mathrm{tr}}^1,d_3^1)\cup p_2^1(p_{1\mathrm{tr}}^1,p_{1\mathrm{tl}}^1,d_3^1)\cup p_2^1(p_{1\mathrm{tl}}^1,p_{1\mathrm{dl}}^1,d_3^1),$$

$$p_{1\mathrm{dr}}^1=p_1^1(d_1^1(p_{1\mathrm{tr}}^1),d_2^1(p_{1\mathrm{dl}}^1),d_3^1),\ p_{1\mathrm{tl}}^1=p_1^1(d_1^1(p_{1\mathrm{dl}}^1),d_2^1(p_{1\mathrm{tr}}^1),d_3^1),$$

$$d_{1\mathrm{dl}}^1=d_1^1(p_{1\mathrm{dl}}^1),\ d_{2\mathrm{dl}}^1=d_2^1(p_{1\mathrm{dl}}^1),\ d_{1\mathrm{tr}}^1=d_1^1(p_{1\mathrm{tr}}^1),\ d_{2\mathrm{tr}}^1=d_2^1(p_{1\mathrm{tr}}^1),$$

where $\circ$ is the operation of gluing concepts [8], $p_{1\mathrm{dl}}^1, p_{1\mathrm{tr}}^1$ are the coordinates of the vertices of the element (Figure 5a), $r_1^{2\mathrm{res\ pr}}$ is the relation "to have a property" of the second layer of the language of the class "resource-property" [9].

The concept "property" $pr^2\in PR^2$ (Figure 5b) is represented by the expressions:

$$pr^2(p_{1\mathrm{dl}}^1,p_{1\mathrm{t}}^1,p_{1\mathrm{dr}}^1,p_5^1,d_3^1)=r_1^{2\mathrm{pr\ pr}}(pr^2,p_{1\mathrm{dl}}^1)\circ r_1^{2\mathrm{pr\ pr}}(pr^2,p_{1\mathrm{t}}^1)\circ r_1^{2\mathrm{pr\ pr}}(pr^2,p_5^1)\circ$$

$$\circ r_1^{2\mathrm{pr\ pr}}(pr^2,d_3^1)=p_2^1(p_{1\mathrm{dl}}^1,p_{1\mathrm{t}}^1,d_3^1)\cup p_2^1(p_{1\mathrm{t}}^1,p_{1\mathrm{dr}}^1,d_3^1)\cup p_2^1(p_{1\mathrm{dr}}^1,p_{1\mathrm{dl}}^1,d_3^1)\cup p_5^1,$$

$$\left|p_2^1(p_{1\mathrm{dl}}^1,p_{1\mathrm{t}}^1,d_3^1)\cap p_5^1\right|=1,\ \left|p_2^1(p_{1\mathrm{t}}^1,p_{1\mathrm{dr}}^1,d_3^1)\cap p_5^1\right|=1,\ \left|p_2^1(p_{1\mathrm{dr}}^1,p_{1\mathrm{dl}}^1,d_3^1)\cap p_5^1\right|..1,$$

where $p_{1\mathrm{dl}}^1, p_{1\mathrm{t}}^1, p_{1\mathrm{dr}}^1$ are the coordinates of the vertices of the element, p_5^1 is the inscribed icon, $r_1^{2\mathrm{pr\ pr}}$ is the relation "to have a property" of the second layer of the language of the class "property-property".

The concept "action" $act^2\in ACT^2$ (Figure 5c) is represented by the expressions:

$$act^2(p_{1\mathrm{dl}}^1,p_{1\mathrm{tr}}^1,d_3^1)=r_1^{2\mathrm{act\ pr}}(act^2,p_{1\mathrm{dl}}^1)\circ r_1^{2\mathrm{act\ pr}}(act^2,p_{1\mathrm{tr}}^1)\circ r_1^{2\mathrm{act\ pr}}(act^2,d_3^1)=p_2^1(p_{1\mathrm{dl}}^1,p_{1\mathrm{dr}}^1,d_3^1)\cup$$

$$\cup p_2^1(p_{1\mathrm{dr}}^1,p_{1\mathrm{cr}}^1,d_3^1)\cup p_2^1(p_{1\mathrm{cr}}^1,p_{1\mathrm{tr}}^1,d_3^1)\cup p_2^1(p_{1\mathrm{tr}}^1,p_{1\mathrm{tl}}^1,d_3^1)\cup p_2^1(p_{1\mathrm{tl}}^1,p_{1\mathrm{dl}}^1,d_3^1),$$

$$p_{1\mathrm{dr}}^1=p_1^1(d_1^1(p_{1\mathrm{tr}}^1),d_2^1(p_{1\mathrm{dl}}^1),d_3^1),\ p_{1\mathrm{tl}}^1=p_1^1(d_1^1(p_{1\mathrm{dl}}^1),d_2^1(p_{1\mathrm{tr}}^1),d_3^1),$$

$$p_{1\mathrm{cr}}^1=p_1^1(d_1^1(p_{1\mathrm{dr}}^1)+0,5(d_2^1(p_{1\mathrm{tr}}^1)-d_2^1(p_{1\mathrm{dl}}^1)),d_2^1(p_{1\mathrm{dr}}^1)+0,5(d_2^1(p_{1\mathrm{tr}}^1)-d_2^1(p_{1\mathrm{dl}}^1)),d_3^1),$$

where $p_{1\mathrm{dl}}^1, p_{1\mathrm{tr}}^1$ are the coordinates of the vertices of the element (Figure 5c), $r_1^{2\mathrm{act\ pr}}$ is the relation "to have a property" of the second layer of the language of the class "action-property".

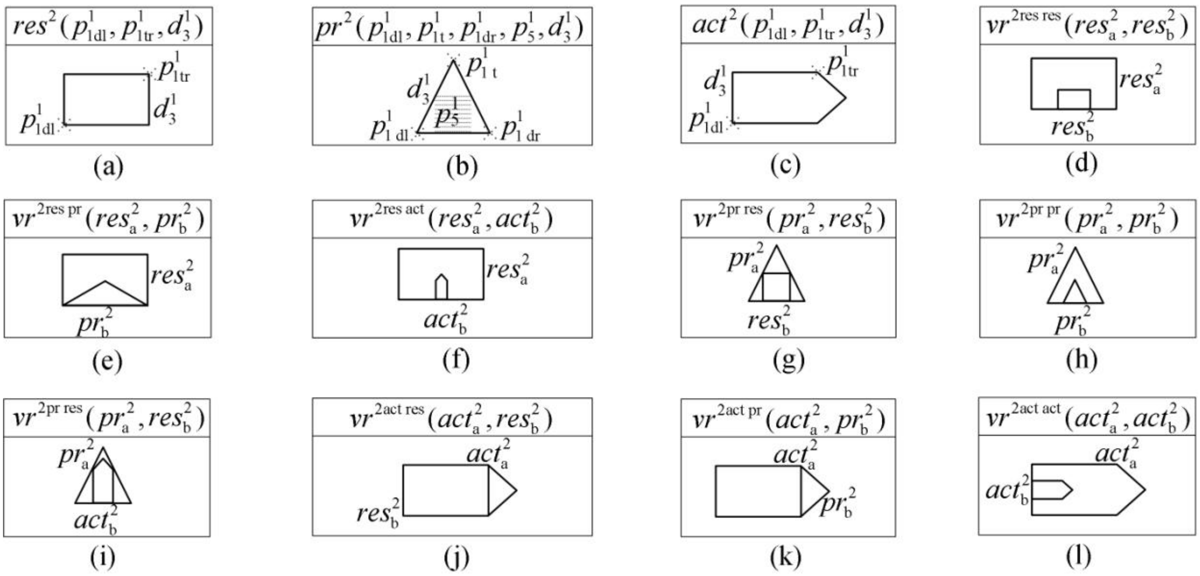


Figure 5. Main graphic elements of the second layer of the conceptual-visual metalanguage: a) resource; b) property; c) action; d) role relation "resource – resource"; e) role relation "resource – property"; f) role relation "resource – action"; g) role relation "property – resource"; h) role relation "property – property"; i) role relation "property – action"; j) role relation "action – resource"; k) role relation "action – property"; l) role relation "action – action".

The visual relation "resource-resource" $vr^{2\text{res res}}(res^2_\text{a}, res^2_\text{b})$ (Figure 5d) is formalized by the expression:

$$\begin{gathered} vr^{2\text{res res}}(res^2_\text{a}, res^2_\text{b}) = \{(res^2_\text{a}, res^2_\text{b}) \mid \forall p^1_{1\text{b}} \exists p^1_{1\text{ah}} \exists p^1_{1\text{al}} (d^1_{1\text{al}}, d^1_{1\text{b}}, d^1_{1\text{ah}}) \wedge \\ \wedge \forall p^1_{1\text{b}} \exists p^1_{1\text{ah}} \exists p^1_{1\text{al}} (d^1_{2\text{al}}, d^1_{2\text{b}}, d^1_{2\text{ah}}), p^1_{1\text{ah}}, p^1_{1\text{al}} \in res^2_\text{a}, d^1_{1\text{ah}} = d^1_1(p^1_{1\text{ah}}),\ d^1_{2\text{ah}} = d^1_2(p^1_{1\text{ah}}), \\ d^1_{1\text{al}} = d^1_1(p^1_{1\text{al}}),\ d^1_{2\text{al}} = d^1_2(p^1_{1\text{al}}),\ p^1_{1\text{b}} \in res^2_\text{b},\ d^1_{1\text{b}} = d^1_1(p^1_{1\text{b}}),\ d^1_{2b} = d^1_2(p^1_{1\text{b}}),\ d^1_1, d^1_2 \in \text{ÿ} \}. \end{gathered} \tag{3}$$

Formalized descriptions of visual relations "resource – property", "resource – action", "property – resource", "property – property", "property – action", "action – action" (Figures 5e-5i, 5l) are analogous to the equation (3) for the visual "resource – resource" relation, therefore, they are not given here. The visual relation "action – resource" (Figure 5j) is represented by the expression:

$$\begin{gathered} vr^{2\text{act res}}(act^2_\text{a}, res^2_\text{b}) = \{(act^2_\text{a}, res^2_\text{b}) \mid p^1_{1\text{adl}} = p^1_{1\text{bdl}} \wedge p^1_{1\text{atr}} = p^1_{1\text{btr}},\ p^1_{1\text{adl}} = p^1_{1\text{dl}}(act^2_\text{a}), \\ p^1_{1\text{atr}} = p^1_{1\text{tr}}(act^2_\text{a}),\ p^1_{1\text{bdl}} = p^1_{1\text{dl}}(res^2_\text{b}),\ p^1_{1\text{btr}} = p^1_{1\text{tr}}(res^2_\text{b})\}, \end{gathered}$$

and a visual relation "action – property" (Figure 5k) is represented by the expression:

$$\begin{gathered} vr^{2\text{act pr}}(act^2_\text{a}, pr^2_\text{b}) = \{(act^2_\text{a}, pr^2_\text{b}) \mid (p^1_{1\text{acr}} = p^1_{1\text{bt}}) \wedge (p^1_{1\text{atr}} = p^1_{1\text{bdl}}) \wedge (p^1_{1\text{adr}} = p^1_{1\text{bdr}}), \\ p^1_{1\text{acr}} = p^1_1(d^1_1(p^1_{1\text{adr}}) + 0{,}5(d^1_2(p^1_{1\text{atr}}) - d^1_2(p^1_{1\text{adl}})), d^1_2(p^1_{1\text{adr}}) + 0{,}5(d^1_2(p^1_{1\text{atr}}) - d^1_2(p^1_{1\text{adl}})), d^1_3), \\ p^1_{1\text{atr}} = p^1_{1\text{tr}}(act^2_\text{a}),\ p^1_{1\text{adr}} = p^1_1(d^1_1(p^1_{1\text{atr}}), d^1_2(p^1_{1\text{adl}}), d^1_3),\ p^1_{1\text{adl}} = p^1_{1\text{dl}}(act^2_\text{a}),\ p^1_{1\text{bdl}} = p^1_{1\text{dl}}(pr^2_\text{b}), \\ p^1_{1\text{bt}} = p^1_{1\text{t}}(pr^2_\text{b}),\ p^1_{1\text{bdr}} = p^1_{1\text{dr}}(pr^2_\text{b})\}. \end{gathered}$$

Thus, the visual primitives (Figure 5), which constitute the alphabet (core) of the second layer of the metalanguage for FHIS of the regional power systems management, are formally defined. On their basis, a set of visual primitives is defined, examples of which are shown in Figures 6a-6d. It’s the dictionary VN^2 of the second layer of the metalanguage. From the primitives in Figures 6a-6d, in turn, the schematic images of resources, properties and actions are constructed as shown in Figure 6e.

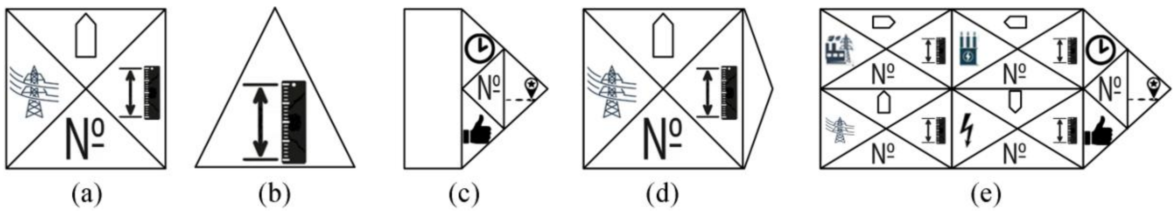


Figure 6. Examples of schematic images of the second layer: a) the schematic image of the resource "air power line" as a four-role visual relation; b) the property "measure"; c) the action "transfer"; d) "means" for the action; e) schematic image of the action "transfer of the object “electricity”, via an air power line, from the CHP, to a transformer substation, start time and end time, name, characteristics, estimates".

These primitives and schematized images can be used as an alphabet in higher-level languages to organize visual reasoning about resource hierarchies, actions, properties, states, situations, etc.

The presence of interconnected formal and visual descriptions of the same entities allows the FHIS, depending on the degree of uncertainty in the decision-making environment, to enable the expert to participate in solving the problem, visualizing the current decision-making situation, and thus to switch between verbal-logical and visual-shaped mechanisms of reasoning.

5. Conclusion

A formal model of conceptual-visual metalanguage is proposed as a multilayered structure which is the basis for the automated solution of problems using integrated verbal-logical and visual-shaped reasoning. An example of the application of the proposed model for describing the alphabet of the metalanguage of operational and dispatching control of regional electric networks is considered.

The use of the proposed models makes it possible to implement FHIS that are able to dynamically synthesize an integrated model and method over heterogeneous model and visual fields and simulate the cooperation, relativity and complementarity of collective intelligence for finding solutions on verbal-symbolic and visual-shaped languages. FHIS of this class will be able to manage the simulation process depending on the uncertainty of the problem situation: when the domain of phenomena is formalized (partially formalized) to use expert knowledge models from a heterogeneous model field to search for solutions, and when there is a significant uncertainty not removed by accurate analysis and logical-mathematical reasoning, to activate the mechanisms of visual-spatial, imaginative thinking of FHIS users.

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