COMPUTER AIDED CONCEPTUAL VISUAL DESIGN BASED ON ONTOLOGY

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Abstract: This paper presents a broad range of ontological aspects that are related to conceptual visual design aided by computer. A formal model of visual design system is defined. In the considered exemplary CAD system based on the model, design ideas are visualized in the form of diagrams created by the designer on the monitor screen. Designer's diagrams are automatically transformed by the system into data structures. Design knowledge encoded in the data structures is transformed into sentences of the first order logic. The obtained logic language enables the system to reason about compatibility of designer's solutions with specified constraints.

1 INTRODUCTION

Computer Aided Design is well-established research area. Contemporary CAD systems, following the Building Information Modelling paradigm, store all project's 3D elements in a central database and are able to generate 2D drawings and 3D renderings (Eastman et al., 2008). Although there are many computational tools for describing, editing, analyzing, and evaluating design projects the application of ontology in CAD is relatively new and problem oriented (Yurchyshyna and Zarli, 2009). This is one of the reason that the initial conceptual design phase, mainly based on ontological knowledge, is very rarely supported by computer. In conceptual design process understanding of requirements goes together with the visualization of early design solution (Grabska, 2010). Visual thinking is supported by cognitive tools, such as computer screen (Tversky and Suwa, 2010). This paper considers a broad range of ontological aspects that are related to conceptual visual design aided by computer. The proposed top-level ontology constitutes a framework for the study of visual conceptual design process and is related to a kind of conversation of designers with their drawings on the monitor screen. On the basis of this ontology an exemplary of the computer-aided design system supporting conceptual design is outlined.

2 FORMAL MODEL

During the conceptual visual design process aided by computer the designer has a kind of conversation with their diagrams. This dialogue can be characterized as the following cycle: drawing diagrams, inspecting them, finding new things (e.g., emergent shapes and/or relations, feedback from the computer system), and redrawing (Goldschmidt, 1994).

The proposed ontology of conceptual visual design aided by computer considers the dialogue in a formal way. To describe this dialogue key concepts are distinguished: a design task t, a visual site v, a physical design action a, and a data structure s. Each design task is classified by requirements which are modified during the design process. A visual site is constituted by a drawing of a design solution and a surface (a cognitive tool) on which it is drawn. Two different drawings on the same surface, e.g., on the monitor screen, determine two different visual sites. A physical design action is one of such operations as drawing, copying and erasing visual elements.

The categorization of sets of key design concepts is given by the notion of classification (Barwise and Seligman, 1997).

Definition 1. A **classification** is a triple

$$D = (O, \Sigma_O, \models_O), \text{ where:}$$

- O – is a set of objects to be classified,
- Σ_O – is a set of types used to classify objects of O,

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- $|-_O$ – is a binary relation between O and Σ_O that specifies which objects are classified as being of which types.

Conceptual visual design is characterized by three relations: a semantic convention =>, signalling $\longrightarrow$, and an input-output relation $\rightsquigarrow$. The first relation => is defined between constraints on visual sites and constraints determined by designer's requirements. The second one $\longrightarrow$ is based on visual perception and determines visual sites used to find a solution of design task (Shimojima, 1996). The third relation $\rightsquigarrow$ is a tertiary one and determines *input* visual site and *output* visual site for a given action.

A formal model of Computer Aided Conceptual Visual Design (CACVD) is defined as follows:

Definition 2. A **CACVD** system is a 5-tuple

$$\mathcal{C} = (\boldsymbol{D_T}, \boldsymbol{D_V}, \boldsymbol{D_A}, =>, \longrightarrow, \rightsquigarrow), \text{ where:}$$

- $\boldsymbol{D_T} = (T, \Sigma_T, |-_T)$ is a classification of a set T of *design tasks*,
- $\boldsymbol{D_V} = (V \times S, \Sigma_V \cup \Sigma_S, |-_V)$ is a classification of *visual sites*, where $V \times S$ is a set of pairs (v, s), Σ_V is a set of types used to classify the visual sites V and Σ_S is a set logic formula supporting the classification of the visual sites, on the basis of data structures of S,
- $\boldsymbol{D_A} = (A, \Sigma_A, |-_A)$ is a classification of physical design actions,
- => is a relation from $\Sigma_V \cup \Sigma_S$ to Σ_T, called a *semantic convention*,
- $\longrightarrow$ is a binary relation from V to T called a *signalling relation*,
- $\rightsquigarrow$ is a tertiary relation $\Sigma_V \times \Sigma \times \Sigma_V$ called *an input-output relation*, $v_i \rightsquigarrow^a v_o$ means that action a has v_i as an *input* visual site and v_o as an *output* visual site.

Signalling relations $\longrightarrow$ together with semantic convention => form a mapping from the set $\boldsymbol{D_V}$ to the set $\boldsymbol{D_T}$. This mapping defines the ontological commitment between visual sites and design tasks.

For all actions a, a' in A and visual sites v, v' in V the composition $a \bullet a'$ is defined by means of an extension relation $\rightsquigarrow$ with the input visual site v and with the output visual site v' in the following way:

Definition 3. $\boldsymbol{v \rightsquigarrow^{a \bullet a'} v'}$ iff there is a visual site v^* in D_V such that $v \rightsquigarrow^{a} v^*$ and $v^* \rightsquigarrow^{a'} v'$.

The **CACVD** system allows one to describe a visual design process and manner in which the designer thinks about design problems. There are two major categories of thinking: *divergent* and *convergent* (Lawson, 2001). Divergent thinking is imaginative and intuitive, whereas the convergent one is logical and rational. Taken as a whole, design is a divergent task. However, during the process of creative design good designers are able to develop and maintain several lines of thought, both convergent and divergent.

The divergent task for designer's mind is an open-ended approach seeking alternative. In our model the definition of divergence is as follows:

Definition 4. Let $\mathcal{C} = (\boldsymbol{D_T}, \boldsymbol{D_V}, \boldsymbol{D_A}, =>, \longrightarrow, \rightsquigarrow)$ be a **CACVD** system and $\sigma_1, \ldots, \sigma_n$ be a sequence of types classifying design tasks of T, and => be a semantic convention. The model **CACVD imposes divergence** on the types $\sigma_1, \ldots, \sigma_n$ iff there exists an input visual site v_i in V and a sequence of actions $a_1, \ldots, a_m$ in A such that:

- The types $\sigma_1, \ldots, \sigma_n$ allow the composition action $a_1 \bullet \ldots \bullet a_m$ on the visual site v_i.
- The output visual site v_o for the action $a_1 \bullet \ldots \bullet a_m$ allows new types $\omega_1^*, \ldots, \omega_k^*$ in Σ_V for $k > 1$ such that $v_o |-_V \omega_i^*$ for all $i = 1, \ldots, k$.
- On the semantic convention =>, each type ω_i^* confirm a type σ of Σ_T or/and can indicate a new type of Σ_T.

In other words, the composition of actions $a_1, \ldots, a_m$ leads to the output visualization site which allows the designer to discover new facts. Each of these fact can inspire the designer to perform one of alternative actions or to formulate a devised requirement. The convergent way of thinking can be defined in an analogical way.

3 CAD SYSTEM BASED ON ONTOLOGY

Assumptions for a CAD system supporting conceptual visual design based on **CACVD** model are as follows:

1. visualizations of early solutions are the main source of knowledge about created designs,
2. these visualizations created by the designer on the monitor screen are automatically transformed into data structures,
3. the system transforms semantic and syntactic information encoded in the data structure into sentences of a logical language forming design knowledge about early solutions,
4. a method of reasoning about compatibility of design solutions with specified constraints is developed.

Figure 1 shows relations between the designer with CAD system and components of formal model. Polygons with grey sides represent common areas. Let us consider some components of an exemplary CAD system based on the ontology which has been developed (Grabska E., et al., 2008). In this system design ideas are visualized by means of diagrams. A *specialized diagram language* consists of a vocabulary being a finite set of *visual elements* and a finite set of rules specifying possible configurations of these visual elements.

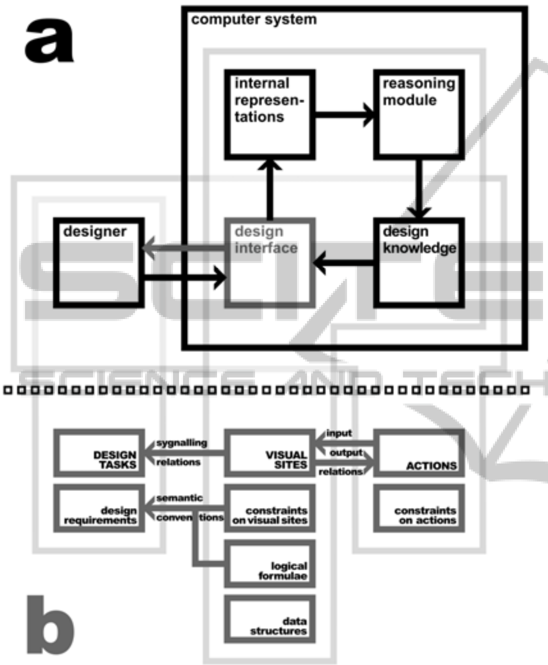

Figure 1: CAD system based on ontology: a) A schema of conceptual visual design system; b) Key concepts and relations of its formal model.

Let us consider a simplified specialized CAD editor for designing floor layout composed of polygons which are placed in an orthogonal grid. These polygons represent functional areas or rooms. A diagram with three component is shown in Figure 2.

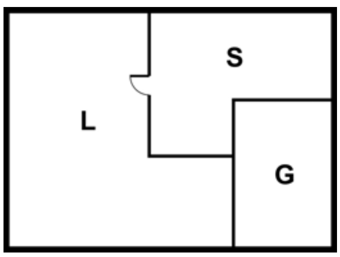

Figure 2: The diagram with three components.

Mutual location of polygons is determined by the designer. The sides of each polygon are ordered clock-wise starting from the top left-most one. In a diagram only qualitative coordinates are used i.e., only relations among graphical elements (walls) are essential.

It is known that graphs are useful for specification of knowledge. In the graph knowledge representation the way of organization, processing and manipulation of design knowledge is based on the spatial relation between objects. Conceptual graphs have been proposed as a knowledge representation and reasoning model (Sowa, 1984). They have been used as a graphical interface for logics. During conceptual visual design process the designer often modifies a design diagram and/or changes design these changes computer readable graph operations and graph rules are defined. Therefore for modelling and modification of knowledge about diagrams we propose to use *hyper-graphs* which can be treated as an extension of conceptual graphs with appropriate structures for local graph transformations.

The proposed hyper-graphs have two types of hyper-edges, called *component* hyper-edges and *relational* hyper-edges. Hyper-edges of the first type correspond to drawing components and are labeled by component names. Hyper-edges of the second type represent relations among fragments of components and can be either directed or non-directed in the case of symmetric relations. Relational hyper-edges of the hyper-graph are labeled by names of relations. Component hyper-edges are connected with relational hyper-edges by means of nodes corresponding to common fragments of connected design components.

Definition 5. Let Σ be an alphabet of labels of hyper-edges and nodes. *An hyper-graph over* Σ is a system

$$G = (E, V, t, s, lb, att, ext), \text{ where:}$$

- $E = E_C \cup E_R$ is a finite set of hyper-edges, where elements of E_C, called *component hyper-edges*, represent drawing components, while elements of E_R, called *relational hyper-edges*, represent relations,
- V is a nonempty finite set of nodes,
- $t: E \to V^*$ is a mapping assigning sequences of different *target nodes* to all hyper-edges,
- $s : E_R \to V^*$ is a mapping assigning sequences of different *source nodes* to relational hyper-edges,
- lb: $E \cup V \to \Sigma$ is a labeling function.

An example of the internal representation of the diagram presented in Figure 2 is shown in Figure 3.

Drawing the diagram the designer specifies labels of components related to room types. While he

designer creates a diagram and/or modifies it using design actions, the hyper-graph is automatically generated.
For each labelled design component in the form of a polygon one component hyper-edge is created.

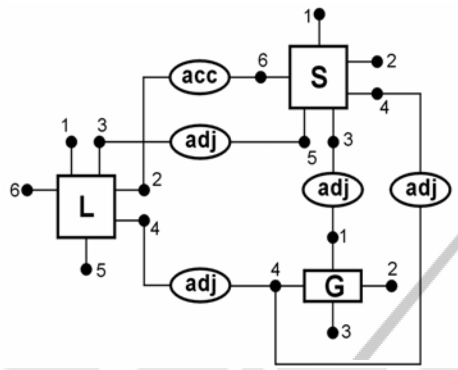

Figure 3: The hyper-graph for the drawing in Fig. 2.

Semantic information about this component describing it as a room is automatically completed by a hyper-edge label describing a type of this room. When the designer divides a component into parts, the hyper-graph composed of component and relational hyper-edges representing the arrangement of these parts is nested in the component hyper-edge representing the divided component. For each line shared by polygons in the diagram one relational hyper-edge connecting nodes representing corresponding sides of the polygons is generated. Semantic information about this relation depends on the line styles and determines the type of the relational hyper-edge label. In the considered example, lines with door symbol on them represent the accessibility relation among components, while continuous lines shared by polygons denote the adjacency relations between them.

During the conceptual visual design process aided by computer diagrams created by the designer and transformed to appropriate hyper-graphs and then translated to sentences of the first-order logic. In this process a problem-oriented relational structure, which assigns elements of hyper-graphs to entities of the specified first-order logic alphabet is used. The design domain of this structure includes: a set of component hyper-edges, and a set of hyper-graph nodes. Relations between design components presented in the diagram are specified between fragments of these components, which correspond to hyper-graph nodes. The interpretation of each relation is the hyper-edge relation of the hyper-graph such that there is a relational hyper-edge coming from a sequence of nodes of at least one component hyper-edge and coming into a sequence of nodes of other component hyper-edges.

4 CONCLUSIONS

This paper is an attempt to present a formal coherent framework for computer aided conceptual visual design aided by computer. Important features of this framework are as follows:

- a distinction between different kinds of knowledge determined by designer's requirements, visual sites, actions, data structures and logical languages,
- a formal description of divergent and convergent categories of thinking,
- a formal description of the fundamentals of visual design necessary to devise CAD-systems and new computer cognitive tools.

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