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SYNTHESIS OF PRODUCT FUNCTION/MEANS STRUCTURES BASED ON VISUAL THINKING

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1. Introduction

Thinking through visual design and images plays always important role in creative activities. In literature, a gift of absolute visual thinking is sometimes identified with the name “autism” and “autistic perception of external world” [www.grandin.com/inc/visual.thinking.html 2000]. Yet, a nature of autism is not well understood. It is evident only the fact that visualization skills enable designers to build products images by taking small parts of these images in their imagination and coupling them together. To create new designs they use visual memory for retrieval of the most essential pieces and combining them into a new whole. Today we cannot mention any computer model of conceptual design, where properties of visual thinking have been somehow realised. In fact, we deal with developing models of verbal thinking in symbols and words. In this sense, basic design images are not considered as mental pictures, but rather as single design concepts concerned with specification of certain design components.

For this reason, an attempt is made in the present paper to propose a more adequate approach to modelling a visual thinking in design. The main feature is the development of cognitive structures for representation of visual images in the form of so called function/means design aggregates. It is also studied what reasoning procedures should be used for coupling these aggregates. Finally, application problems of visual thinking with respect to the collaborative web conceptual design are discussed.

2. Visual perception of design images

Human consiciousness involves two mechanisms of thinking, such as a verbal and a visual thinking. The first mechanism is intended to work with abstract chains of symbols and words, whereas the second mechanism operates with visual images of external world and representations about them. The better understanding the difference between both mechanisms is achieved in analysing the process of visual images perception at the moment of design knowledge acquirement. Whilst a verbal thinking creates a single valued context of percepting original design image, a visual thinking enables to create multivalued context of the same design image by covering a variety of its functional, physical and behavioral properties.

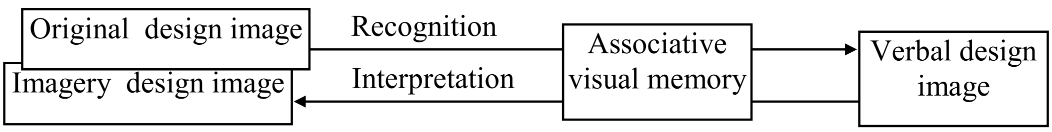


Figure 1. General scheme of images visual perception

The process of visual images perception can be formally considered as a mapping of original design image (ODI) into pseudo-original design, or imagery image (IDI) having the certain behaviour. As shown in figure1, one can extract two stages of this process:

- Image recognition (ODI → VDI);
- Image interpretation (VDI → IDI),

where VDI denotes verbal design image received as a result of routine processing ODI data, e.g. as a result of its entity generation, entitlement and classification as a single whole.

Thus, acquired at the first stage *verbal knowledge* is conventional set of information for creating computational models and models of conceptual design based on verbal thinking. However, in order to create a model of visual thinking, it is necessary to acguire *visual knowledge* captured as a result of the interpretation of verbal knowledge. This is possible provided that the model of visual memory has associative cognitive structure and interface adapted to interprete VDIs within basic concepts of design domain investigated. One of the aims of this paper is to specify requirements and to describe general version of such model. Other aim is to describe application of visual knowledge for synthesis of function/means structures in mechanical domain.

As regards the direct mapping (ODI → IDI), it represents the case of absolute visual thinking, or the pathology known in medical literature by the name “autism”. It defines the human uncapacity to images verbalization, and therefore cannot be used in models of intellectual design.

3. The problem of visual thinking

The most commonly understood aspect of visual thinking is the designer ability to reproduce a product image in the mind by selecting smaller PDIs, taking them for basic components and coupling together. Therefore the main problem is to develop computer methods and tools for:

- Explicit representation of visual knowledge in form of IDIs;
- Coupling the basic IDIs into a single whole;
- Contextual matching the different IDIs.

Being remained within the problem solution concerned with only the synthesis of product structures we derive from the following definitions.

ODI is detailed structure of design image, which is composed from the total list of its components. Of course, this representation doesn’t support the creative aspects of visual perception.

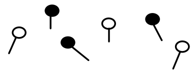
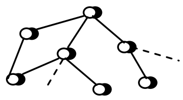
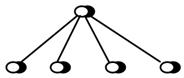
VDI is resulted from ODI by removal of all its design components, i.e. VDI is intelligible concept used to denote design image as a single whole.

At last, IDI is enlarged structure composed from the limited number of the most important components of design image. Other words, it is *compositional interpretation* of VDI based on creative vision of design image. In the paper, IDIs are considered as *fuction/means design aggregates* having certain contents and behaviour. Represented in the form of standard two-layer structures these are captured as a result of passing design images through certain cognitive perception structures and the interface described in the next section.

This implies the central idea that a product structure can have not only the verbal image synthesized from basic VDIs, but the compositional image too. Based on using design aggregates the last one differs from the verbal image with larger compactness and comprehensibility. Especialy, it is important for exchange of knowledge in web environments.

In literature, principles of structural synthesis are usually presented by bottom-up approach, e.g. morphological synthesis [Pahl 1996], case-based reasoning design [Pulm 2003], and by top-down approach, e.g. functional design [Stone 1999], configuration design [Pavlic 2001] and others. However, analysis reveals that none of bottom-up methodologies contributes anything to our understanding the visual thinking because of missing steps concerned with compositional interpretation of basic design concepts and cases. Partial exception is top-down approach, where interpretation steps can be associated with mental decomposition of design images (means) into structural constituents during the design process. Particularly, in using a methodology of functional design, the decomposition process is performed over sequential splitting design functions on subfunctions, i.e. basic functions and means are considered independently with each other. Certainly, this is conflicted with ideas of visual thinking. On the contrary, in using a methodology of configuration design, the decomposition process is virtually coincides with interpretation process, but it is always performed within the same preset structure, i.e. a product configuration. This is also unacceptable condition for visual thinking.

Table 1. Comparing methodologies of synthesizing function/means structures

Basis concepts and components used	Symbolic representation of basic concepts and components	Methodologies used to synthesize purpose function/means structures
Functions, Means		Morphological synthesis, Functional design
Function/Means Design Cases		Configuration design, Case Based Reasoning (CBR) design
Functio/Means Design Aggregates		Compositional design based on visual thinking

Comparing these methodologies like in table 1, we have motivated the necessity to develop so-called *compositional method* of product structures synthesis. Formally, compositional method can be represented as top-down extension of the purpose function/means aggregate being taken for one of working hypothesises of product image. Here, the contextual relations between all aggregates are supported by analogy with functional design. In section 5, this process is described more in details.

4. Compositional interpretation of design images

Associative visual memory operates on the basis of mental representations derived from images of last. Mental representations of design images depend on the designer's extant knowledge, his self-development, show state, background and other factors used to select and transform new information. Visual knowledge is therefore seen as something that is actively constructed during the process of compositional interpretation in terms of basic cognitive structures in the mind and computational procedures that operate on those structures.

In the proposed approach, a role of general cognitive structure plays a network frame-based product data structure (PDS) created to interprete ODIs in the representation layers of mechanical assemblies (A), subassemblies (S) and machine parts (D). According to PDS model each of these layers provides a way of ODIs partition into certain number of class functions such as:

- (A) *driving, transference, fixing, adjusting;*
- (S) *driving/rotate, transference/move, fixing/position, cathing,…;*
- (D) *rotating, moving, limiting, sealing, controlling,… .*

Concrete meaning of ODI is open over hierarchical relationships established between class functions of adjacent layers. Hence, we can define three types of basic cognitive structures to approach the compositional interpretation of ODIs. These are:

- (A-S) class function structures to interprete assemblies;
- (S-D) class function structures to interprete subassemblies;
- (D-C) class function structures to interprete machine parts,

where C denotes the lowest layer of PDM related to definition of machine part design features.

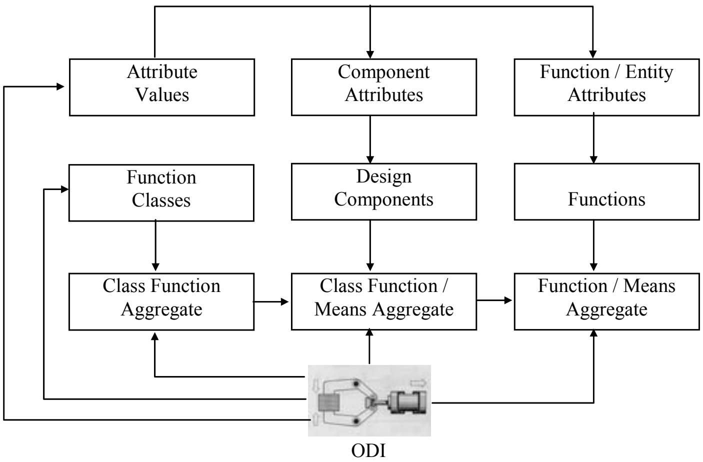


Figure 2. Main stages of compositional interpretation process

Here, it is necessary to proceed from the limited number of hierarchical relationships (e.g., no more than four) in each cognitive structure like the following:

(A-S) *driving [<driving/rotate>, <driving/move>, <catching>, <mating>];*

(S-D) *transference/move [<moving>, <positioning>, <sealing>, <limiting>];… , and so on.*

In total, we have defined within PDS model about 30 interconnected basic cognitive structures [Napalkov, 2005]. Being separate fragments of PDS, these structures look like to "short scenes" within each of which some "acts of a play" should be performed. In failing a scene, acts turn into nonsensical ones. It follows that we can consider basic cognitive structures as class frames that contain slots and template facets to represent explicitely design aggregates over corresponding instance frames.

Figure 2 illustrates three forms of their explicit representation in accordance with different stages of critical understanding of design images during interpretation process:

- Class Function aggregate (CF-aggregate);
- Class Function /Means aggregate (CF/M-aggregate);
- Function/Means aggregate (F/M-aggregate).

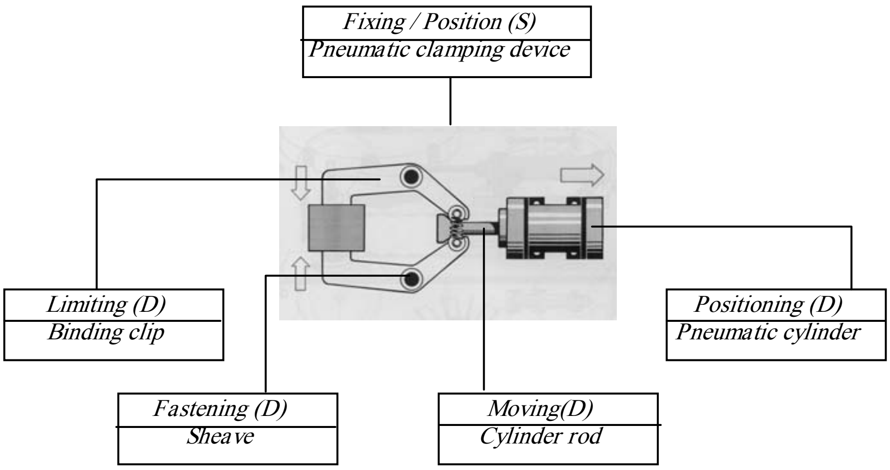


Figure 3. Explicit representation of Class Function / Means aggregate ("Pneumatic clamping device")

The first stage is aimed, on the one hand, to select the design concept that defines the functional entity of considered ODI as a single whole. On the other hand, it is required to match this concept with vertex class function of the most adequate cognitive structure.
At the second stage, the most important design components of ODI are defined according to concepts and meanings of subordinate class functions of the selected cognitive structure. Besides, the designer has to set component attributes and their rating values that exert influence on behaviour of ODI. For example, shown in figure 3 the CF/M-aggregate has behaviour that depends on following design attributes: *Diameter of Pneumatic cylinder*, *Stroke length of Cylinder rod*, *Opening angle of Binding clip*, and others (these are not indicated in figure for simplicity).
At the third stage, the designer has to set concrete functions for design components and ODI as a whole. Being instances of existing class functions each of concrete functions is characterized by its entity (such as "*force*", "*power*", "*signal*", or "*material*") and entity attributes (e.g., *Force type*, *Pressing force*, *Load tension*, *Unit pressure*, etc.). It is necessary to select only those entity attributes and rating values which allow one to have all data for simulating behaviour of the F/M-aggregate with a help of standard application software. For our example, the behavior of *Pneumatic clamping device* can be simulated by diagrams of *Pressing force* in dependence on changing values of above-mentioned design attributes.
Each design component of ODI may have own ODI which is interpreted as F/M-aggregate at the lower representation layer. If some design components have so called "null image", this means that these components are considered as F/M-aggregates at the higher representation layer.
The described interpretation process is executed in interactive mode. To support it the most of design concepts within PDS should be connected with each other through relationships like "many to many". In this case, the PDS model will be able to save F/M-aggregates having:

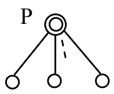
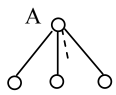
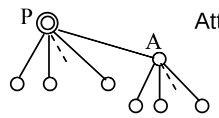
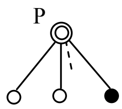
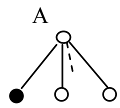
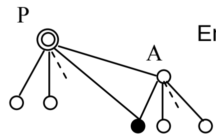
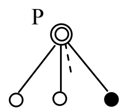
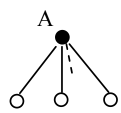
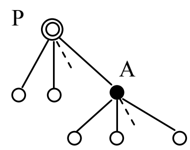
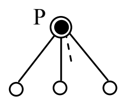
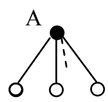
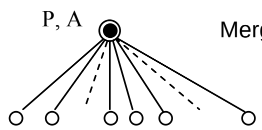
- Different compositions, but the same ODI;
- The same composition, but different ODIs.

Thereby, the support of creative aspects of visual perception in multivalued context is provided for.

5. Top-down extension of function/means aggregates

Following the compositional method of design we deal with the problem solution of covering the user functional requirements and design constraints by minimal function/means graph synthesized from a number of most suitable F/M-aggregates. From a viewpoint of visual thinking, this problem can be considered as top-down extension within some (A-S), (S-D), or (D-C) cognitive structures in designing some assembly unit, subassembly, or machine part respectively. Thus, the feature is that top-down extension applies only to (k-1)-th representation layer with respect to the purpose F/M-aggregate of k-th layer. Therefore a graph of the extended assembly unit can include only subassemblies and other assemblies, a graph of the extended subassembly can include only machine parts and other subassemblies, and a graph of the extended machine part can include only design features and other machine parts.
In order to model this process is to follow the rules of contextual matching F/M-aggregates including their functional compatibility and compositional coupling. The first rule is: "two F/M-aggregates can interact with each other provided that their functions have the same entity, or their entity attributes have specific values in the connection point (port)". This rule is obligatory condition for execution of the second rule that represents different techniques of compositional coupling in dependence on structural features of F/M-aggregates. As illustrated in table 2, there exist four cases according to the application of "attachment", "embedding", "substitution", and "merging" technigue.
Attachment technique is applied in case of only functional compatibility of F/M-aggregates.
Embedding technique corresponds to a case of coincident concepts used for specifying subordinate design components of F/M-aggregates being coupled.
Substitution technique is applied provided that the considered design component of previous F/M-aggregate (P) has null image, but its concept coincides with the concept used for specifying the vertex design component (design image as a whole) of addition F/M-aggregate (A).

Table 2. Compositional techniques of coupling two F/M aggregates

Previous F/M aggregate (P)	Addition F/M-aggregate (A)	Representation of techniques applied
		 Attachment
		 Embedding
		 Substitution
		 Merging

Merging technique corresponds to a case of coincident concepts specifying vertex design components of F/M-aggregates with different ODIs.

Based on using these compositional techniques the process of synthesizing product function/means structures can be described by the main steps as follows:

- Retrieving F/M-aggregates whose components have maximal membership with functional requirements and design constraints inquired in the user query including the purpose function of a product being designed;
- Retrieving addition F/M-aggregates whose components have maximal membership with the rest functional requirements and design constraints;
- Pair coupling addition F/M-aggregates with previous F/M-aggregates;
- Validation of the composed function/means graph.

Here, the rules of fuzzy logical retrieval evaluating local membership degree of each design component and total memberhip degree of each F/M-aggregate with regard to the user query should be applied for making relevant design decisions [Napalkov 2004].

At the step of pair coupling F/M-aggregates, the main criterion is to achieve maximal connectivity of design components with each other. This corresponds to the problem statement of synthesizing a function/means structure with minimal number of graph nodes. Then a number of design iterations is essentially decreased during the design process, and a danger of initiating so called "information explosions" typical for function design is disappeared. For that, the different schemes of compositional synthesis can be proposed such as sequential, concurrent (pair replacements), genetic, combined, and other compositional schemes.

The result of top-down extension is addition of new functionalities to the specification of purpose F/M-aggregate. Thus, the next important problem is to capture validation rules for proving truth or falsity of composed design solutions. We believe that one of possible approaches can be concerned with a check of opportunity to enforce the purpose behaviour on all new design components. However, this problem goes beyond of present research. Therefore, it is suggested that the designer enables himself to validate design solutions, to reject them in case of necessity, and to initiate the generation of new design solutions derived from selecting new working hypothesises.

6. Case study for web collaborative design

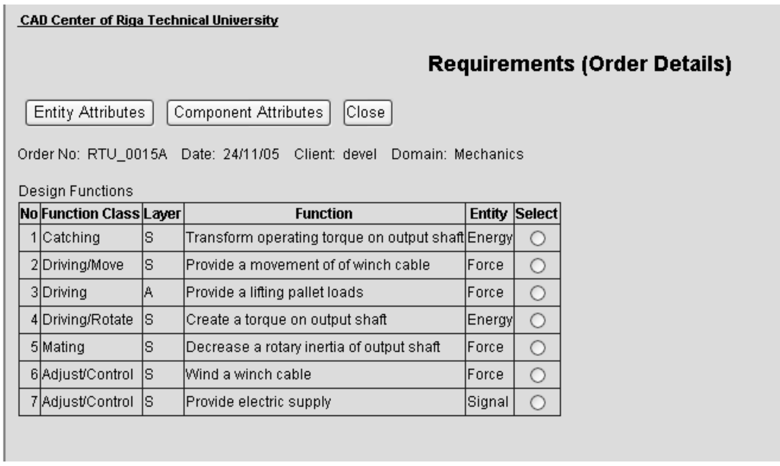
The design process within virtual collaboration requires extensive exchange of design knowledge among involved partners, especially at early phases of design. The main barrier is incompatibility of information formats used in different product data models. Mostly, to solve this problem the federated conception of sharing and managing design information is applied [Wang et al. 2002]. This approach is based on patching heterogeneous databases together to create some middleware infrastructure that provides autonomy of collaborative partners during the design process. Thereby, each of them solves certain subtask in general task of collaborative design. A major disadvantage is that a product configuration must be submitted in advance, i.e., be preset.

More flexible approach is to provide autonomy of the design process on the basis of visual knowledge collective support in shared information environment. Toward this end, we have developed the model of visual knowledge management (VKM) enabling remote designers to interact with each other through authorized access to the PDS model described above. According to the federated principle each remote designer work independently in his home information environment, but he can interprete his visual knowledge in terms of PDS cognitive structures to provide the coherence with other tasks being solved. In this view, VKM is considered to be linked to strategies of visual knowledge acquirement and reuse. These strategies are:

- Codification of design concepts used for explicit representation of F/M-aggregates;
- Maintenance of a library of FM-aggregates having the behaviour required;
- Maintenance of a library of design solutions specifying the user queries.

Gathering, editing, and preparing different kinds of information for own purpose within the PDS context the designer makes this information available to those who need it. Thus, a common interest of all involved partners is to intensify the application of these strategies for visual knowledge exchange to reuse them for improving a quality of own design solutions.

The way to employ VKM in shared information environment corresponds to the way to use WWW. There is the VKM navigation menu accessing to necessary information over queries and other user actions. Example of Web page for representation of query in form of certain set of desired functions, their attribute values and design constraints for retrieving relevant design solution is shown on fig. 3.


CAD Center of Riga Technical University

Requirements (Order Details)

Entity Attributes | Component Attributes | Close

Order No: RTU_0015A Date: 24/11/05 Client: devel Domain: Mechanics

Design Functions

No	Function Class	Layer	Function	Entity	Select
1	Catching	S	Transform operating torque on output shaft	Energy	○
2	Driving/Move	S	Provide a movement of of winch cable	Force	○
3	Driving	A	Provide a lifting pallet loads	Force	○
4	Driving/Rotate	S	Create a torque on output shaft	Energy	○
5	Mating	S	Decrease a rotary inertia of output shaft	Force	○
6	Adjust/Control	S	Wind a winch cable	Force	○
7	Adjust/Control	S	Provide electric supply	Signal	○

Figure 4. Web page for representation of user query

If available solution variant is not found in a library, then a Reasoning Engine of VKM is activated to synthesize this solution in form of function/means structure. Therefore, the more a volume of visual knowledge base within PDS model the higher quality of design solutions can be achieved during the design process.

7. Conclusions

This paper has described a role of compositional approach for synthesis of product function/means structures. Allowing the notion of imigary design image (IDI) we have elaborated the way of its explicit representation in form of so-called FM-aggregate. This way lies in compositional interpretation of original design images having a behavior. In order to interprete design images the different cognitive structures have been described. Based on using FM-aggregates the design process has been defined as similar with visual thinking. The main contribution is the development of methodology for compositional synthesis of design solutions based on modelling the process of top-down extension of purpose FM-aggregate selected. To support these processes we have described four techniques of compositional coupling FM-aggregates such as attachment, embedding, substitution, and merging technigue. The proposed approach is attractive for several reasons:

- It helps the designer to generate a design solution during smaller number of iterations in contrast to other top-down methods (e.g. functional design);
- It allows the designer to apply combinatorial shemes of compositional synthesis to synthesize optimal structures of products;
- It enables designers to collaborate with each other by resorting to compositional interpretation of own visual knowledge in terms of single cognitive structures.

Future work is application of compositional approach for Web collaborative design based on using VKM model described.

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