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MODELLING FUNCTIONALITY OF DESIGN PATTERNS BY MEANS OF FUZZY FRAMES

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Abstract: *The problem of functional modelling during the design process requires a linking design functions with the structural and physical embodiments of design objects. Knowledge of objects functionality tends to be rule-based systems because any inference precedes sequential logic. There are a variety of methodologies dealing with the functional design. In this paper the emphasis is placed upon the application of fuzzy logic rules within the common product data model represented in the form of fuzzy frame-based network. The feature is the integrated approach to modelling functionality, in a search mode, via matching behavioural actions to organ structures of designs.*
Keywords: *Functional Modelling, Design Organ, Fuzzy Frame, Membership Function*

1. INTRODUCTION

Functional modelling is one of the most important design activities. It aims at composing design constituents so as the assembled mechanical product could provide the desired function. Based on a search of suitable ways of transforming the desired function to the product behavioural description, this approach remains until now the leading technique of conceptual design.
According to [Pahl & Beitz, 1996] the behaviour can be represented as input-output action that includes some functional requirement (driving input), a principle of solution, mechanism or some design component (behavioural actor) and intended output action (functional output). Given functional requirements, main output functions and imposed constraints a complex behavioural scheme is constructed from simple behaviours as the result of causal decomposition of functional inputs, in reasoning manner. The main strategy is to search all intermediate behaviours whose functional outputs can achieve the desired output functions. Thus, the product structure is determined once the behavioural scheme is fixed. Nevertheless, in solving some design problems, essential difficulties are arisen. These problems include: design in large solution spaces, design in dynamic environment, design within the context of multiple engineering tasks, and others. In particular, we deal with similar problems in design by supporting the Common Product Data Model (CPDM). Therefore, the development of modified methods based on the integration of functional modelling with other kinds of models is required. The goal of this paper is to describe an integrated approach allowing one to approximate the desirability of design functions and behaviours by a set of fuzzy logic rules.

2. FRAME-BASED REPRESENTATION OF THE BEHAVIOR

Past developments of the CPDM have mainly focussed on the component structure. An underlying construct behind this approach was the template or prototype used for creating both the actual product and the design components representing it (Murdoch et al., 1997).
In the proposed approach, a role of the template plays the frame intended for description of none one but different classes of design components. Connected with each other into multilevel network, such frames are capable to solve many problems of analysis and synthesis capturing descriptions of function, behaviour and structure in different domains of design. In this case, a complex behaviour is represented by organ structure. It is one of possible superimposition on the component structure making the product suited for its life phases.
An organ structure consists of minimal number of design organs, whose graphical images annotate their form and operation principle. They are generated as the result of interaction among so-called class frames and instance frames. While the class frames are intended for representing general functions of the CPDM and their hierarchical relationships, the instance frames are required to represent design organs themselves. Really, as shown on Fig.1, a simple behaviour in the CPDM depends on collection of functional requirements related to input general function on the one hand, and the given attribute values, on the other hand.
It means that functional requirements and constraints define the design organ entitle, but attribute values define a graphical image, i.e. the design pattern of this entitle.
In the mechanical product the design organs can be distributed on a few hierarchical levels corresponding to description of machines, assemblages, subassemblies and parts. Here, the most important patterns of assemblages are taken for design organs to describe machines. By analogy, the most important patterns of subassemblies are used as design organs for assemblages, and so on including a description of chosen machine surfaces as design organs for parts (Napalkov & Zars, 2003). When composed, they result in both vertical and horizontal organ structures in accordance with causal decomposition of design functions.

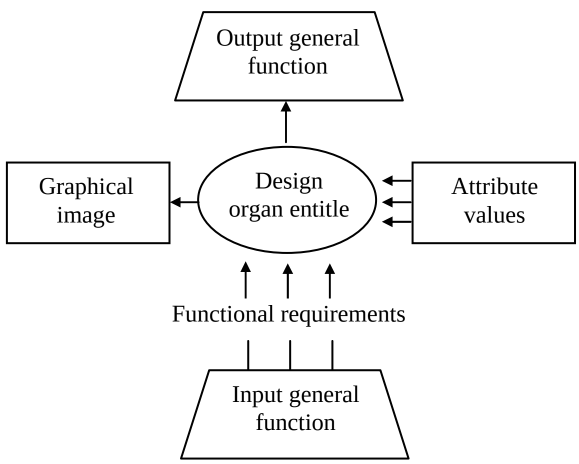


Fig. 1. Model of the frame-based behaviour

3. CAUSAL DECOMPOSITION OF GENERAL DESIGN FUNCTIONS

To model the functionality of design organs, the causal decomposition should be realized via description of class frames. At the highest level, the class frame allows one to represent the global mechanical function of any machine as certain type of physical energy generated as a result of impact of following input general functions:

> *Mechanical* [<*driving*>,<*adjusting*>,<*transference*>, <*fixing*>].

In turn, these input functions (listed in brackets) are used for modelling the functionality of assemblages. In particular, each of them realizes certain type of energy transformation, which is initiated by appropriate collection of input general functions described as follows:

> *Driving*[<*driving/rotate*>,<*driving/move*>, <*catching*>,<*mating*>];

> *Adjusting*[<*adjusting/control*>,<*adjusting/limit*>, <*catching* >, <*mating*>];…, etc.

In modelling the functionality of subassemblies, each of them can be considered as some class of mechanical relations between parts represented by following way:

> *Driving/rotate*[<*rotating*>,<*positioning*>, <*controlling*>, <*limiting*>];

> *Driving/move*[<*moving*>,<*positioning*>, <*controlling*>, <*limiting*>];

> *Catching*[<*rotating*>,<*moving*>,<*limiting*>, <*fastening*>];…, etc.

At last, in modelling the functionality of parts, input functions are used to specify machine surfaces influenced on the part typification, its basing, clamping and counteracting to different loads, for example:

> *Rotating*[<*operation/rotate*>,<*clamping/rotate*>, <*guide-bearing*>, <*reinforcing*>];

> *Positioning*[<*operation/position*>, <*clamping/position*>,<*guide-bearing*>, <*reinforcing*>];…, etc.

In total, 22 class frames have been used for representation of the CPDM functional structure and modelling behaviours of mechanical products. For more detailed representation of class frames, all general design functions are divided into smaller functions saved in separate facets. At the same time they are considered as functional requirements. One can set different functional requirements within the same general functions. For example, regarding the motor mechanics the function "*adjusting/control*" can be divided into parts such as:

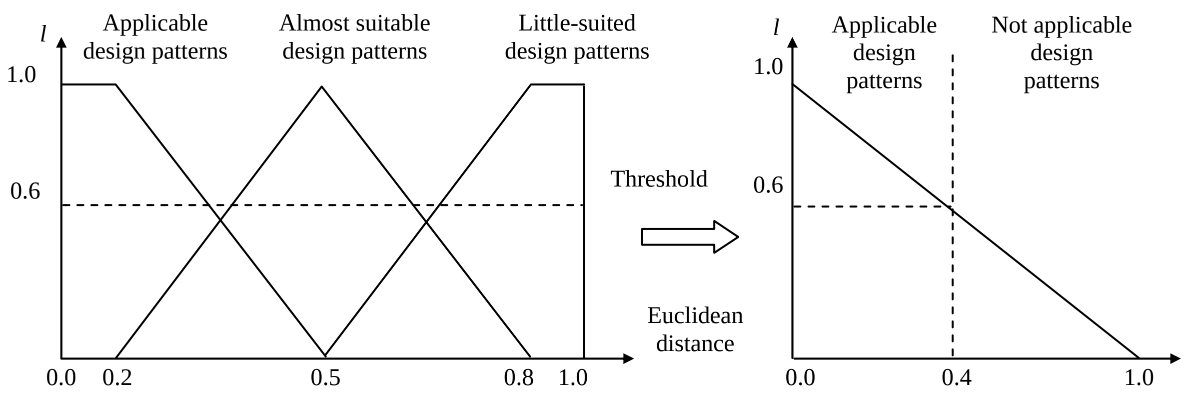
> *Provide a forced supply of lubrication oil;*
> *Provide a circulation of refrigerating fluid;*
> *Provide a fuel feed under pressure; …*, etc.

It follows that the design organs, i.e. the causes of these functions should be different types of pumps with attribute values and patterns described in appropriate instance frames. Depending on a domain application the definitions of smaller design functions can be changed in wide range. However, there exists a danger of information explosion in deducing inferences. This occurs because of partial uncertainty of selecting both design organ classes and their graphical images. Since the class frames are intersected in the developed version of the CPDM, we enable to extend essentially a search area of relevant decisions, but the uncertainty becomes more too. Therefore, the development of additional tools is required for removal of unnecessary decisions. As analysis revealed this problem solution can be easier by means of fuzzy frames application.

4. FUZZY FRAMES APPLICATION

As usually, the notion of "fuzzy frame" is introduced in storing multiple values of an object attribute in the form of fuzzy variables (also called the linguistic variables) (Yager, 1999). The advantage is a gradual transition in real values associated with design attributes. When used in the network an additional opportunity is also appeared to evaluate relationships between design organs by implementing the properties of multiple inheritances and classifications during the design process.

Let $((p,c),\omega)^j \in [0,1]$ be a weight of the pair $(p,c)^j$, in which the attribute p is matched with the image c of some design organ belonging to the jth general function. Then the total weight $(c,\omega)^j$ of the image c about the user query q can be



a) Input membership functions

b) Output membership function

Fig. 2. Membership functions used in fuzzy rules

expressed in form of the Euclidean distance $d\ (c,q)^{j}$ between them defined as

$$(c,\omega)^{j} = \sqrt{\sum_{p} \| (p,c),\omega)^{j} - q \|^{2}}\ , \qquad (1)$$

where operation of summation is performed by identifying the specified attributes p of the image c; $(p,c)^{j} \in (P^{j} \times C^{j})$.

Allow a set of such images $C^{j} = \{(c,\omega)^{j} / c\}$, and the membership function

$$f\colon C^{j} \times C^{j} \to [0,1] \qquad (2)$$

to evaluate the similarity degree $f\ (c,\omega)^{j} = ((c,\omega),\ l)^{j}$ of each image in respect to the user query q, where l is a value of linguistic variable, $C^{j} \subseteq C$.

For that, one can divide the set C^{j} into clusters according to three terms of a linguistic variable such as "little-suited", "almost suitable" and "acceptable" images about the user query. These terms and values of linguistic variable l evaluate the similarity degree of image c by evaluating its membership degree with each of above-mentioned clusters.

As shown on Fig.2a we have used for clustering the two trapezoidal and one triangular membership functions with three critical points (0,2, 0,5, 0,8) within the common interval [0,1] of measuring the Euclidean distance. It makes easier the test operation because the sum of membership degrees into the three linguistic values will always be equal to 1 for any point within the common interval under such representation of membership functions (Zadeh, 1997).

Let $(((c,\omega),\ l)^{j},\ s)^{i}$ denote the membership degree $((c,\omega),\ l)^{j}$ of the image c taken for design organ of the image s, belonging to the ith general function. Then the total membership degree $((s,\omega),\ l)^{i}$ of the image s can be computed by means of superposition operation defined in following way:

$$((s,\omega),\ l)^{i} = \sup_{j} \{(((c,\omega),l)^{j}, s)^{i} / c\}\ , \qquad (3)$$

where superposition operation includes:

- interpolation of local membership functions to define the term and value of the total linguistic variable l for the image s;
- defuzzification of local membership functions to define the total similarity degree ω for the image s.

The interpolation process is performed provided that basic structure of rules (like IF-THEN) was built regarding the terms of total linguistic variable. For our goal, it is enough to use only one output term represented by a truncated triangular membership function (Fig.2b). Therefore, the restricted number of basic rules (up to15) is required to describe all combinations of input terms for weighting design organs. An example of one of such combination is:

IF $((c,\omega) / appl)^{1} \wedge ((c,\omega) / appl)^{2} \wedge ((c,\omega) / alm.suit)^{3} \wedge ((c,\omega) / littl.suit)^{4}$ *THEN* $((s,\omega)^{i} \in [0,1])$,

subject to membership degrees are computed with satisfactory threshold of applicability (a value 0,6 is applied), and upper indexes 1,2,..,4 correspond to the output functions of design organs selected (because we have accepted that the total number of design organs cannot be more than 4 in each organ structure).

In the process of defuzzification, a computed value of output membership function is automatically transformed in the Euclidean distance, for example:

IF $((c,\ 0.18) / appl)^{1} \wedge ((c,\ 0.12) / appl)^{2} \wedge$
$((c,\ 0,45) / alm.suit)^{3} \wedge ((c,\ 0,80) / littl.suit)^{4}$
THEN $((s,\ 0,489)^{i} \in [0,1])$,

that allows the system to select only relevant organ structures, in particular, subject to $(s,\ \omega)^{i} \le (s,\ 0,4)^{i}$.

Let a set $S^{i} = \{(s,\omega)^{i} / s\}$ be the ith class of relevant and defuzzificated patterns, and $\omega_{i} = \varphi\ (S^{i} \times S^{i})$ be the weight-average Euclidean distance between all pairs of such images. Then the fuzzy logic task of optimal decision-making can be defined as:

$$\text{Find } \{(s^{*},\omega^{*}),\ \ge\} / \omega^{*} \le \min \varphi\,(S^{i} \times S^{i}),\ \forall I \qquad (4)$$

where $\{(s^{*},\omega^{*}),\ \ge\}$ is an ordered collection of relevant images belonging to different classes of design patterns.

5. STEPS IN THE PROCESS OF DEDUCING INFERENCES

In contrast with functional design based on top-down decomposition of functions, the described approach involves also the bottom-up chain of inferences to retrieve graphical image of organ structure with the target output function. Besides, in order to extend the retrieval it was accepted to involve strategies of multiple classifications and multiple inheritances into common algorithm of design. The first strategy allows the retrieval of target organ structure image in different class frames. The second strategy is aimed on the retrieval of design organs among images, whose functions are invalid with respect to the parent class frame. Therefore the common algorithm of deducing inferences includes much number of iterations. The following are some of the main steps.

1. Defining the target output function of design in accordance with the user query.
2. Listing the possible entitles of organ structures for the given target function.
3. Identifying the causal inputs (which are the output functions of design organs) for the regular organ structure.
4. Testing the adequacy of causal inputs about the given functional requirements. Reversing to the step 3 in a case of existent unavailability.
5. Retrieval of design organs with adequate output functions.
6. Evaluating graphical images of design organs about the user query parameters by using fuzzy logic rules.
7. Structural filtering the design organs to form valid organ structures in accordance with existent instances of its graphical images.
8. Selecting the design pattern with optimal organ structure according to (5).

During the retrieval process, a lack of images related to some entitles of design organs is allowed. It requires a jumping the system on higher level of the CPDM to continue the retrieval of the same entitles, which can be matched with other class frames. Thus, the strategy of multiple inheritances should be applied. Once this class frame is found, a new cycle starts to build the regular branch of inference tree corresponding to creation of subordinate organ structure. Such situation is shown on Fig. 3, where the target function is formulated as *define the assembly mechanism enabling to transform the end-to-end motion into rotary motion*, and where an image of the design organ entitled as *gas-distribution device* has to be built as the result of deducing the subordinate organ structure.

The design process is finished provided that all found images of design organs would satisfy both functional and parametrical requirements. According to our example, the found target organ structure is defined like *crank mechanism* consisting of design organs such as *piston group, crankshaft, cylinder block,* and *gas-distribution device*.

If the system cannot select the target image for valid organ structure, it means the need of creating new design pattern on a base of found graphical constituents. If the list of functional

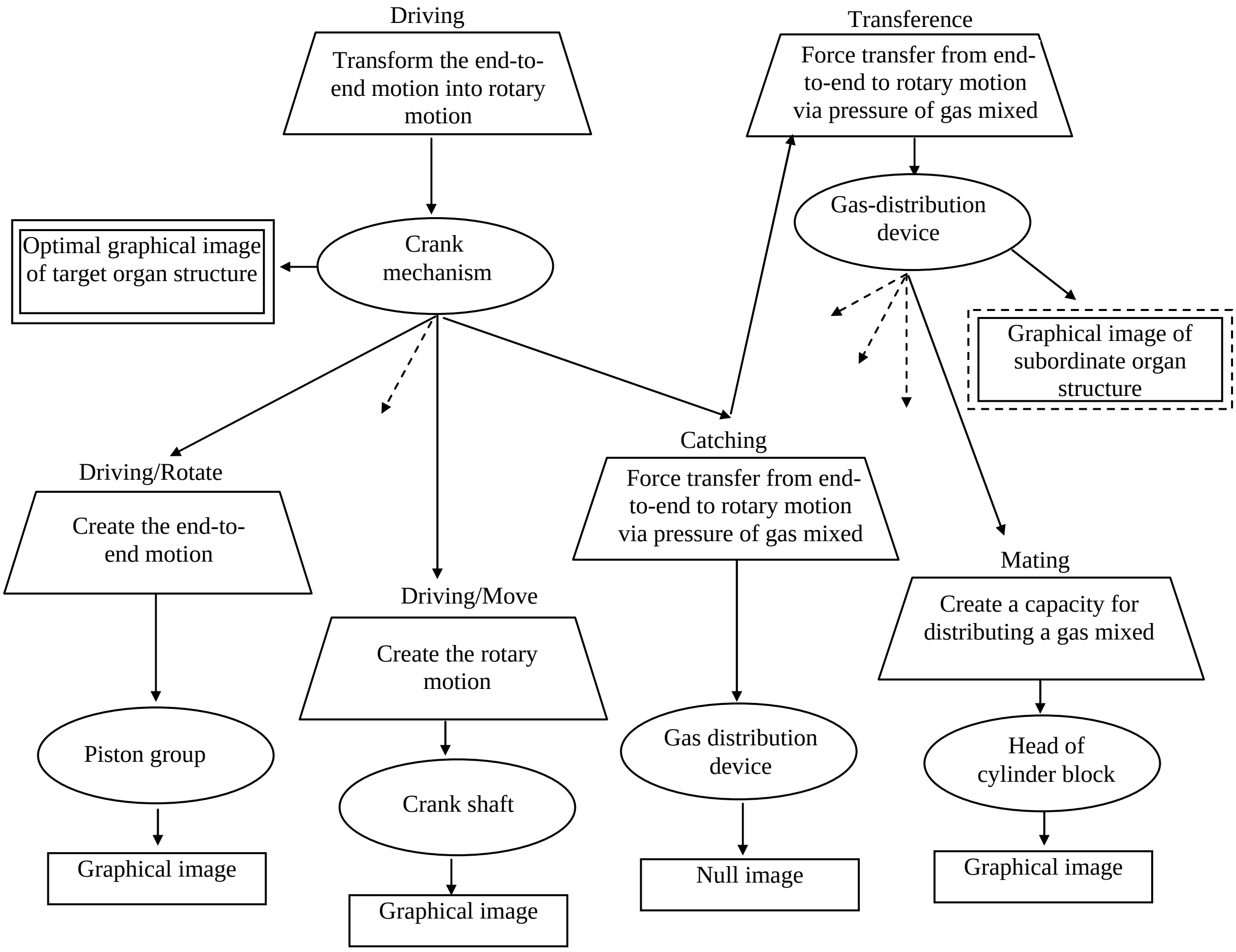


Fig. 3. Example of deducing inference tree for the functional requirements given

requirements are not enough for deducing the complete organ structure the system has to operate in hypothesis generation mode. In this case, each hypothesis is presented to the designer for its confirmation. At last, if the system cannot deduce valid organ structure for the given functional requirements it means that the task has not solutions.

It should be noted that the problem of deducing valid inferences could be matched with computer supporting the process of graphical annotation of design patterns borrowed from external information sources. In this regard, the borrowed design pattern is always considered as fuzzy object that can be portioned by alternative collections of functional and parametrical properties. Therefore the defuzzification of these properties with a help of developing so-called annotation rules must play important role for the CPDM maintenance and for future research in the given area of interest.

6. CONCLUSION

The described method of fuzzy modelling the functionality of design patterns is applied for capturing, structuring and analyzing engineering information required for conceptual design of mechanical products. For this goal, the multilevel fuzzy frame-based model of CPDM is created to interpreter the behaviour and function properties of design patterns in wide ranges. Current research has been focused on casual decomposition of design functions and the development of fuzzy logic rules for selecting relevant graphical images in accordance with functional and parametrical requirements.

It was indicated the necessity of integrating a top-down and bottom-up models of reasoning to make valid decisions. For that, the algorithm based on application of strategies of multiple classifications and multiple inheritances is developed. The main advantages of the described method are high flexibility, accuracy and representation of design patterns in the form of inference trees as a result of the design process.

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