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INTRODUCING NUCLEUS AS A MODELLING ENTITY FOR PRODUCT DESIGN

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1. Introduction: beyond features

The industry is already using the third generation of the CAD/E systems. The first generation of these systems were drawing systems using 2D or 3D curve and symbolic entities to represent a part or an assembly of a product. The second generation is based on volumetric and boundary primitives, such as blocks, cylinders, spheres and surfaces, respectively. The third generation systems are based on predefined or used defined volumetric and/or surface features that are catalogued in libraries and increase the semantic level of modeling. Seeing these changes, we can conclude that one of the aspects of the improvement of the CAD/E systems is the evolution of the modeling entities. Nowadays, this issue is becoming more and more important as the application field of the CAD/E systems expands to conceptual design. The root of the problems is that the conventional modeling entities have been developed to support detail design and the downstream applications rather that conceptual design. They are definitive entities that have nothing to do with the uncertainty, incompleteness and ambiguity, which are typical characteristics of conceptual design processes and conceptualized artifacts. However, the potential to cope with these properties is strongly requested from the modeling entities and modeling methods proposed as the basis of a computer aided conceptual design system.

The fourth generation of CAD/E systems is supposed to have modeling entities which are not only able to cope with vagueness, but also support modeling structures, physical processes and behavior, and changes in the operation processes. Moreover, they are expected to have a kind of evolving nature and provide synergism in terms of modeling the components, the assembly and the whole artifactual system of a product. Since there is a continuing shift towards collaborative virtual design environments, which represent the fourth generation of CAD/E systems, the modeling entities should facilitate creative collaboration, shared model building, and multi-site imagining. Intensive research is going on to expand the functionality of the conventional modeling systems and to introduce brand new approaches. The extension of the feature techniques to conceptual design proved not to be feasible due to the strong need for parameterization, the large number of requested views that have to be integrated, and the lack of support of evolution of the representation [Brunetti 2000]. Non-nominal shape modeling techniques [Yamaguchi 1993], [Ruzák 2000] have been introduced together with physical-based behavioral modeling techniques [Kiriyama 1991], [Bouma 1993], [Janssons 2000]. We hypothesized that capturing and formalizing the design-oriented human concepts and high-level design concepts to modeling entities can open up new opportunities for supporting conceptual design. In our Integrated Concept Advancement (ICA) research program we are looking for theories and methodologies that will support us to realize our hypothesis. We believe that very high-level modeling (VHLM) entities composed from some fundamental constituents can incorporate sufficient amount of knowledge for a knowledge-intensive support of conceptual design.

2. Elaboration on the notions

A novel approach to conceptual modeling of products necessarily introduces new concepts, notions, terms and words that need to be defined, explained and put into context. Below we give a conscise overview of the most fundamental notions and relationships.

Our modeling methodology tries to capture design concepts and formalize them for processing by a computer-based knowledge-intensive system. The term 'design concept' is related to human problem solving, and can be intuitive or learnt concepts. A concept circumscribes a specific part of an existing or imagined reality. From the aspect of knowledge processing, concepts are meaningful individual logical units of reasoning, and implies implies some sort of modeling and representation. Further characteristics of design concepts are their abstractness or concreteness, and their simpliciality and compoundness. The semantic contents and contexts establish associations among the design concepts, that is in harmony with the associative nature of the human brain. Even the simplicial design concepts are too complex to represent exhaustively from all design aspects (geometry, morphology, structure, material, phenomena, behaviour, and life cycle). The complexity problem accompanying the formal representation and handling of design concepts can be coped with by following the reductionist approach, i.e. disintegrating the totality, and reintegrating the formalized elements.

We wish to represent design concepts as units of knowledge reusable for various design problems and situations. The formal representations of design concepts will be referred to as very high level modeling (VHLM) entity. VHLM entities are specific chunks of knowledge that are primarily ingredients of an artifactual model, rather than of the process of artifact creation. This is an important statement from the point of view of finding the relevant ingredients that enable us to capture the content of a design concept. The simplicial design entities typically create relationships between two objects in order to realize a conceived operation. The relationships can be multitude and diverse. They can be reflexive, injective, bijective and transitive. The objects in general have physical extent and material properties. The subsolution represented by the design concept will show different behaviour depending on the arrangements of the objects and the relationships. This abstract interpretation enables us to create a conceptual model of a design concept. It is shown in Figure 1.

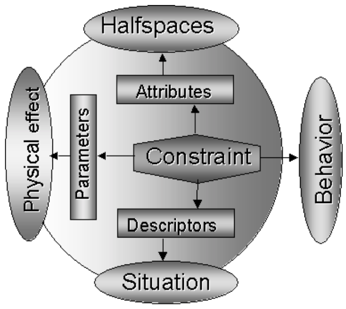

Figure 1. The formal model of a design concept

With symbolic terms, a design concept can be formalized as $DC = \{O, \phi, S, C, A, D, P\}$, where O = involved objects, A = attributes of objects, ϕ = physical relationships, P = parameters describing the relationships, S = situation, D = descriptors of situation, C = constraints on attributes, parameters and descriptors. If any one of objects, relationships and situations is not specified, this abstraction cannot have the potential to be a model of a design concept. Therefore, we call the $N = \{O, \phi, S\}$ triplet nucleus of the design concept. A simplicial design concept consists of at least one nucleus. A compound design concept is a purposeful composition of finite number of nuclei. The objects are metric entities, which can be characterised for their shape and volume. That is objects are understood as points surrounded by an oriented differential surface. Form a mathematical point of view, the shape is depicted by half spaces. At least one half space (H) should be specified for a nucleus. The operation described by a design concept depends on the nature and interaction of the incorporated nuclei, the observable behaviour $B = f(CP)$ is the changes presented by the design concept as a solution element of an artifact model. Based on this terminology, we call our modeling approach a nucleus-based conceptual modeling of products.

Naturally, the designers are not faced these abstract concepts and terms when they are using a nucleus based system in conceptual design. For the sake of the convenient practical use, nuclei are realized as physically coupled pairs (PCP), notions well accepted in physics and engineering and a system of static and dynamic constraints. One of the advantage of the nucleus concept is that the designer is supported in his thinking about the necessary relationships, that the concrete geometry of the artifact, which can be a by product of the nucleus-based design process. The other advantage is that the nucleus based modeling is tolerant to incompleteness, impreciseness and ambiguity, and support multiresolution representation that is inevitable to follow the evolution of the design. A PCP can be formally described as follows: PCP = $\{HS_i, HS_j, R_k, S_l\}$, where HS_i is called a native halfspace, HS_j is called complementer halfspace, R_k is the set of relationships, and S_l is the set of possible situations. Examples for the concrete realization of the PCP-s is shown in Figure 2.

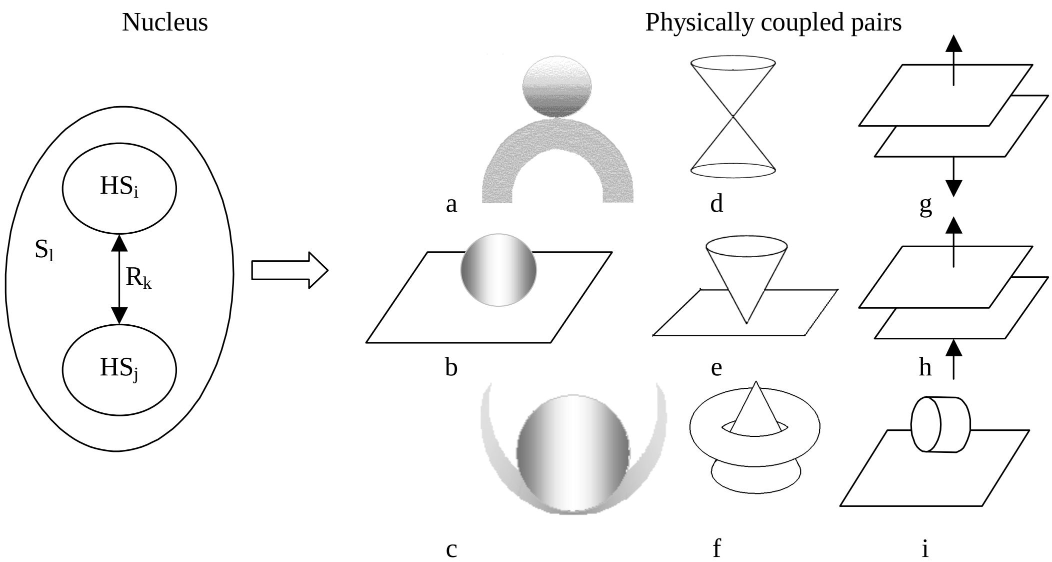

Figure 2. Various realizations of a nucleus as PCPs

The reference point and the differential surface can be used to define the spatial positions and geometry of the half spaces. The reference points can also be used as contact points in between two objects (i.e. half spaces). When half spaces are composed to form a component (part of a product) the geometric and physical relationship between the half spaces are graphically represented as connection lines. This way the geometric modeling with half spaces and connecting lines is traced back to the concept of skeleton modeling. It allows as to assign also physical interpretation to the above defined geometric elements. The reference points are the effect points of some physical phenomena the half space patches are the effect surfaces (both called ports), and the conecting lines are the pieces of the skeleton. The objects included in a nucleus are characterised not only from a geometric point of view, but also for physical properties. That is the half spaces are attributed by geometry dependent, geometry related and geometry independent properties. Physical effects are caused by physical phenomena such us gravitational, mechanical, tribological, thermal, hydraulic, pneumatic, etc. The mechanical phenomena can sustain pressures, forces, moments, impulses, deformations, velocities and accelerations, etc. The full range of effects extends to, but is not limited to tribological, thermal, hydraulic, pneumatic, electric, magnetic, optical, etc., effects.

3. The process of nucleus based modeling

The ultimate goal of this research is to provide a solution for handling multiple design concepts in an abstract form and to develop a unified modeling methodology that covers component, assembly and product modeling. The research is also aimed to solve the problem of multi-aspect handling of component, assembly and product (system) ideas as they evolve in interaction in the conceptualisation and embodiement parts of the product development process. Hence, it is also a goal of the research to provide evolving representation of the concepts in the course of design. In our ICA research program, we develop a process model of evolving artifact definition based on the cognitive scheme of conceptualization. This cognitive scheme specifies human ideation, representation, and reasoning as interrelated actions in the process of conceptualization. Ideation is to generate novel concepts or look for known concepts based on the mental activities of designers. The externalization of the mental models of the ideas creates external representations which can be of altarnative forms (verbal, graphical, phyiscal, etc). The ideation and representation are accompanied by both common sense and expert reasoning, which controls the process of conceptualization, the formation of the artifact and provides feedback to the designers.

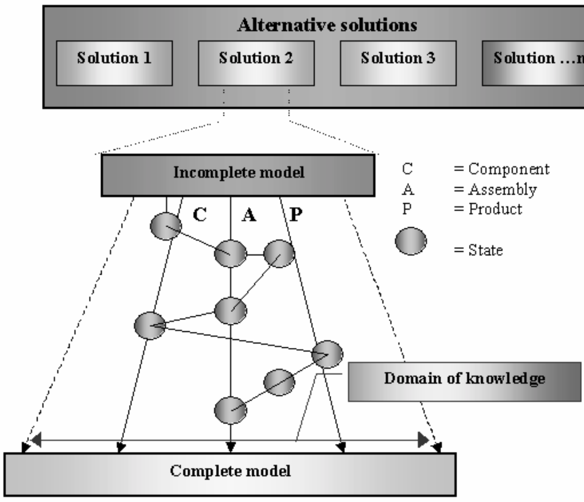

Figure 3. Process flow developed based on the cognitive scheme of conceptual design

Artifactual modeling in conceptual design can be realized through an interrelated development of the artifact on component, assembly and product levels simultaneously, handling multiple variants of design solution, and handling the incomplete solutions as well (Figure 3). The solution of a design problem starts with generating many incomplete conceptual models. Afterwards, these incomplete solution variants are gradually concretized in terms of the geometry of the components, the morphological and structural relationships among them to form assembly connections, and operation as an artifactual system. The concept of nucleus lends itself to an evolving computer representation; the designer has to specify the requested relationships between the elements of a hypothesized component or an assembly, which may be done by means of the development of relation schemes. These can be incomplete both on component and assembly level as well as the geometric definitions of the components and the assembly. The designer works in a multitude of component views, assembly views, and product views and can swap over these evolving representation as he wishes. As far as the specification of the shape of the components is concerned, from a methodological point of view it happens through the levels of generic, global, local and specific shapes. Similarly, relationships can be defined as links, connections, effects, and situations. This way the process of conceptualization is covered by an evolving model that integrate the artifact representation and the process representation. This model will be referred to as a evolving multiresolution model.

Working with an evolving multiresolution model of the product, a designer may start to solve the conceptualization problem either by making effort to define components, describing the assembly as a structure, or specifing physical effects by using physically coupled pairs. The computer aided conceptual design system is supposed to take care of the interrelations between these levels. A component is defined as a purposefully arranged set of nuclei. The definition of the components can be complete or incomplete. The nuclei give the opportunity to immediately specify assembly relationships when part of a component is determined. The physical relationships between nuclei makes it possible to represent the changes that are supposed to occur in the components and in the

connections of components. The physical effects and the cuased changes make it possible to represent the operation of the product, and to simulate its behaviou as a system.
In a physically coupled pair, half spaces represent the boundary of a materialized region of a component and serve as an effect surface for physical phenomena. The situation, which describes a given set of half-spaces and physical phenomena in a given arrangement, will be changed whenever either the attributes of the half-spaces, the physical effects, or the situation itself alter. The changes of the situation the physically coupled pairs are defined in the model can be aggregated to describe the internal changes in parts (e.g. deformation, fracture, etc.), and the internal changes in the product (e.g. kinematics movement, state changes, etc.). This situation oriented representation of the changes in operation is not, or only partially, existing in current CAD/E systems.
In the context of multi-level modeling (component, assembly, and product) the nucleus supposed to handle each level. The geometry of a component is generated as a combination of halfspaces. An assembly model is arranged from components based on structural, morphological, and geometric relationships. A product is derived from an assembly model by taking into account the behavioral changes of the assembly. Structural relationships define the existence and interactions of halfspaces, morphological and metric ones specify the form, degree of freedom, position, and direction of the involved as well as the distances, angles between points and curvatures at points.

4. Principle use of nucleus entities for modeling in practical implementation

A supporting theory is needed to explain (a) how a design concept can be decomposed, (b) to what constituents it can be decomposed and (c) according to which laws it can be decomposed. This is especially important because design concepts are somewhat abstract and not directly accessible for common-sense reasoning. Below we present an example for the decomposition of a simple product (a tin opener) into design concepts, and the representation of the design concepts as arrangements of nuclei.

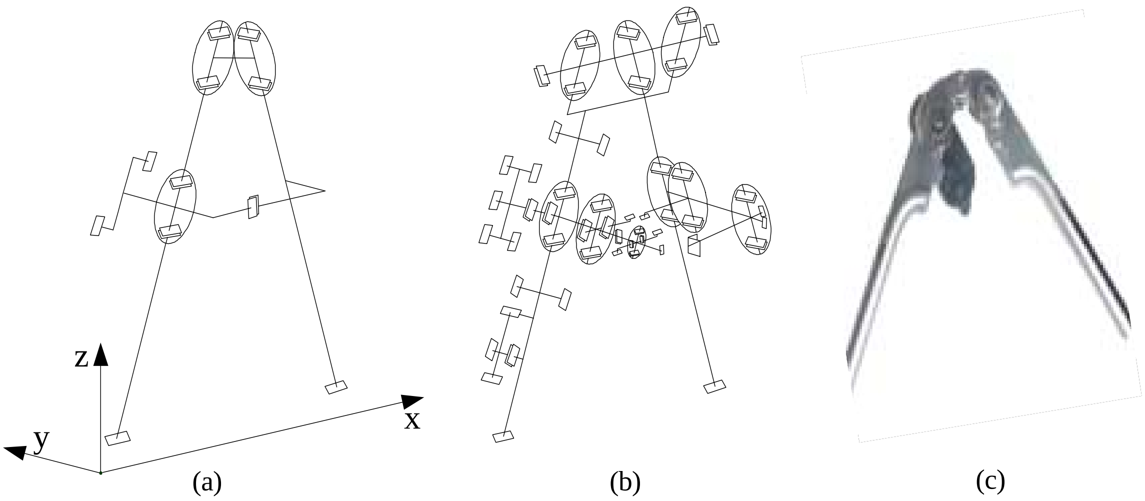

Figure 4. Utilization of the nucleus concept

There are three types of structural relationships in PCP (i) direct internal coupling (DIC), (ii) direct external coupling (DEC), and (iii) indirect external coupling (IDEC). Internal direct coupling is supposed to describe the arrangement of particle clouds. External direct coupling is supposed to describe particles cloud in direct physical contact (in touch) between the elements of different components. Finally, indirect external coupling bring paticle clouds into connection that elements of different components, but have no direct physical contact. Nevertheless, their relationship is important for the operation of the system.
Other type of relationships that could be taken into account, such as material physical and behavioral relationships, are intended to be included in future step of research. Material relationship defines the physical and perceived properties of the material regions. Physical relationship defines the occurring

physical effects in the product operating as a system. Behavioral relationship defines the causality and manifestation of behavioral changes due to physical phenomena. The mentioned relations above are geometrically described by using skeleton modeling technique. It is shown in Figure 4. For further details about the theory and methodology of skeleton modeling can be found in [Horváth, 1995 a and b].

5. Conclusion and future research

In this paper a new modeling entity called 'nucleus' has been introduced. In implementation phase, the physically coupled pairs concept was adopted. This approach will give the opportunities in the future to develop a system that can cope with the incompleteness, umbiguity representation and handle the knowledge evolution. This research will go on with detail development for the application of nucleus concept in components, assembly and product levels.

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