SEMI-AUTOMATIC SYNTHESIS OF CONCEPTUAL TECHNICAL SYSTEMS

Janez Rihtaršič[a] **and Roman Žavbi**[b]

[1] *University of Ljubljana, Faculty of Mechanical Engineering, Aškeréeva 6, 1000 Ljubljana, Slovenia.*
Email: [a]*janez.rihtarsic@lecad.fs.uni-lj.si,* [b]*roman.zavbi@lecad.fs.uni-lj.si*

The article presents a semi-automated approach to the synthesis of conceptual structures of technical systems. Technical systems are man-made and function exclusively on the basis of physical, chemical and biological laws (i.e. natural laws). Compared to the working principles and components, the advantage of the application of the physical laws is that the physical laws enable a more elementary level of presenting the technical system. On the basis of the effects of one or more physical laws, it is possible to build a range of diverse components and a number of working principles. Understanding the physical background of a technical system allows better structural design already in the conceptual phase. The focus of this paper is structural visualization of automatically generated conceptual technical systems.

Keywords: Product development, Conceptual design, Synthesis, Physical law, Basic schema.

1. INTRODUCTION

From the product development point of view the search for solutions for given requirements and their structural embodiments is probably the most creative, but also responsible part of the design process. One of the main problems of many methods and tools used to support conceptual development phase is unclear connection between the functional domain and the structural domain. Abstractness of this phase presents a major hurdle and also a challenge for computerized algorithms. Main motivation for presented research is overcoming this hurdle to enable automatic generation of conceptual technical systems for a desired function.

First systematic approaches used function structures and morphological matrices, which were the basis for structural synthesis of technical systems [1, 2]. More precise identification between various parts of components and functions was made possible with introduction of organs [3]. Organ consists of one or several wirk elements, which are usually located on different parts of a technical system. Places at which the technical system receives or delivers effects of physical laws are called wirk elements. Wirk elements (point, line, surface, volume) present the organ structure, which is needed for realization of the desired function. Term "wirk element" is borrowed from the German language where it was also firstly mentioned; alternative names for wirk elements are effective elements, function carriers or half spaces. However, organ structures are not explicitly defined and as such are difficult to use in automated structural synthesis. Some computerized methods overcame this hurdle with the use of components or standard parts. Components can be used for generation of a conceptual technical system as well as for its optimization [4].

In the following semi-automated approach the structural synthesis is enabled with the use of physical laws and complementary basic schemata [5]. Each physical law has only one basic schema. A physical law defines the relations between wirk elements within the basic schema. The main difference between the organ and the basic schema is that basic schema contributes only to realization of a particular

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physical law, which is often not sufficient for realization of the complete function. As chains and more complex systems of physical laws can provide the necessary effects for function realization of the technical system, so can chains and more complex systems of complementary basic schemata constitute the necessary structure of such technical system.

In the research presented here, we use the above mentioned approach to semi-automatically generate technical systems and their structures. In the rest of the paper we will shortly describe the method (section 2) and generate several conceptual solutions for a technical system that can remove a toll sticker (vignette) from a car windshield (section 3). The process of embodiment will be explained in section 4. Results of the case study are discussed in section 5 and the paper concludes with the summary of the method in section 6.

2. METHOD

Technical systems consist of a matter, which interacts when stimulated by certain physical quantities (i.e. causes). Resulting physical effects propel technical processes needed for realization of desired functions.

To start the search for needed physical effects we need to specify available physical laws and desired input physical quantities. Physical laws are connected into chains of physical laws [6]. The chaining algorithm is based on the idea of binding physical laws and their complementary basic schemata (i.e. sets of wirk elements) via binding quantities. A binding quantity is a quantity common to a physical law and its successor in a chain. The result of chaining is a chain, which represents an elementary product concept and describes the transformation of the input quantity to the output quantity (i.e. an abstract description of the mode of action). Chaining is regarded as a search for and synthesis of physical laws and complementary basic schemata into structures, which are capable of realizing a required function.

A typical problem associated with automated generation of conceptual technical systems is one of combinatorial complexity [6]. The problem of combinatorial explosion becomes relevant when a computer tool generates a huge number of solutions. In such cases the number of solutions would become unmanageable during the phase of their analyses.

There is a positive correlation between the number of generated alternative product concepts and their quality [7], so it makes sense to further develop formal methods that would enable the generation of alternative concepts. This statement was empirically confirmed by comparison of automatically generated conceptual solutions with the number of finally selected (i.e. "promising") solutions (Figure 3). However practical experiences also show that design engineers prefer to generate conceptual technical systems manually instead of evaluating several thousand or even hundreds of thousands of automatically generated solutions.

Tools for automatic generation of design ideas tackle the problem of high number of generated solutions in two ways (i) by setting restrictions before ideas are generated and (ii) by evaluation and selection of design alternatives from generated ideas.

The latter approach is used in a tool called the designer preference modeler [8]. The computational synthesis tool generates design alternatives using a catalogue of design knowledge formulated as grammar rules, which describe how electromechanical designs are built. A designer engineer, on the other hand, gets involved in the process by evaluating a prescribed set from these design alternatives. The design engineer's feedback is translated into a preference model that is used to automatically search for best designs. Because the preference model is built directly from the evaluations of a design engineer, it reflects the designer's reasoning and judgment under specific design objectives and constraints. Design engineer's preference model is constructed from limited number of design engineer evaluations, which can then be used for evaluating large number of design alternatives.

Approach presented in this paper uses both ways for generation and selection of automatically generated conceptual technical systems. Figure 1 represents the number of solutions with respect to the number of physical laws contained in a chain.

Empirical analysis has shown that the use of this method does not lead to a combinatorial explosion [6]. Relatively small number of physical laws (139) and prohibition of repetition of a physical

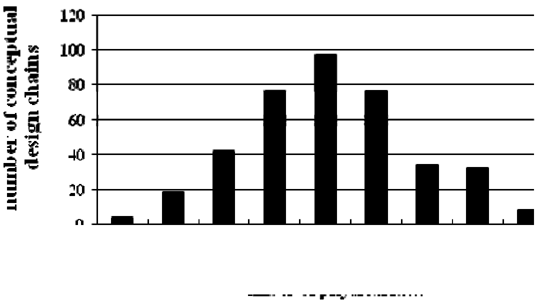

Figure 1. Bell shaped histogram of a family of conceptual design chains for force as output effect [9].

law within a solution chain results in bell-shaped histograms. Additional control options were built into the computer tool to enable further reduction of the number of generated solutions and to improve their quality (see Idea generation section). It seems that the combination of computing and human reasoning is becoming the common property of different tools for automatic generation of conceptual technical systems.

3. IDEA GENERATION

Generation of a conceptual technical system starts with a selection of physical domains and physical laws, which would provide effects for fulfillment of a function for which the technical system is going to be designed. Further, the maximum number of physical laws within a chain is defined (chain length). Based on experiences gained so far it is most time-wise optimal to generate chains up to 3 laws in a chain. Number of solutions up to this length is still relatively small and they already point out majority of possible working principles. Specification of input/output physical variable has also significant impact on the number of generated solutions. There are three possible input/output patterns: (i) specified input/specified output, (ii) specified input/unspecified output and (iii) specified input/specified output. If an input/output variable is not specified than all output/input variables contained in selected physical laws are possible, which consequently results in increased number of solutions.

In the following step a list of chains of physical laws is automatically generated. Number of generated solutions is at this point reduced by scanning the list of solutions and by excluding not wanted physical laws, input and output variables and generated chains. The chains of basic schemata are generated simultaneously with the chains of physical laws. A chain of basic schemata represents a starting point for structural synthesis of the conceptual technical system. More detailed information about the computer tool, which is based on the described method, can be found in literature [10].

4. STRUCTURAL SYNTHESIS

Basic schema contains information on physical quantities and structural elements needed for realization of a complementary physical law. Relations between physical quantities and wirk elements inside a basic schema are specified by a physical law. Every basic schema has at least one input physical quantity (cause), one output physical quantity (effect) and one wirk element. If a physical law requires more physical quantities and wirk elements for realization of its effect, than complementary basic schema will also have additional physical quantities and wirk elements. Constituent elements of basic schemata and shaping properties of wirk elements are more precisely described in literature [5]. In the process of embodiment, wirk elements are shaped manually, but the relations between physical quantities and wirk elements (as generated automatically) must be maintained (see Figure 4). For more complex technical systems (i.e. with more than one function) several chains of basic schemata are combined to form a structure of a complete technical system. Some physical quantities can be common to several physical laws in different chains of basic schemata. There also might be effects of different physical laws, which take place on the same element. They share this particular element. Both types of connections (physical and structural) enable generation of complex system of physical laws and a complex system of basic schemata.

Structure sharing is said to be observed in a product, when more than one function is performed by the same structure at the same time and it is claimed to make a product more resource effective [11].

In the presented approach the structure sharing is clearly established when connecting the basic schemata within the chain of basic schemata and between different chains of basic schemata. When the "map" of future technical system is generated the design engineer proceeds with final embodiment of the conceptual technical system. At this stage previously application-neutral wirk elements are being shaped manually.

5. CASE STUDY

In the following study a design engineer was given a task to generate conceptual technical systems for removal of a toll sticker from a car windshield. Similar to the examples shown in [11] the function structure for intended conceptual system was developed (Figure 2). Technical system should enable heat generation to reduce adhesion force between the sticker and the windshield. Further it should be able to detach the sticker and remove it from the windshield.

For sub functions the physical effects (Heat, Force, and Displacement) needed for their fulfillment were defined. For these effects the solution chains were automatically generated. Based on experiences (as discussed in the section: Idea generation) we limited the chain length up to three physical laws in a chain. Set of 139 physical laws was used for chaining. For the more detailed description of computer tool see reference [10].

Within the pool of solutions the most promising chains were selected. Although the correlation between generated and selected chains is not linear, the histograms from the Figure 3 empirically confirm positive correlation between the number of generated alternative product concepts and their quality, as proposed in [7]. The number of automatically generated solutions was reduced by scanning through the list of generated solutions and by excluding not desired physical laws or not desired chains. When excluding one physical law, all chains which contain particular physical law were excluded.

1. For the heat effect all together 1769 chains were generated from which 11 chains were selected as potentially applicable.
2. For the force effect all together 7834 chains were generated from which 30 chains were selected as potentially applicable.
3. For the displacement effect all together 10385 chains were generated from which 42 chains were selected as potentially applicable.

Each chain represents different working principle for solution of a desired effect. With activation of a chain of physical laws the complementary chain of basic schemata is activated in the structural synthesis module (Figure 4).

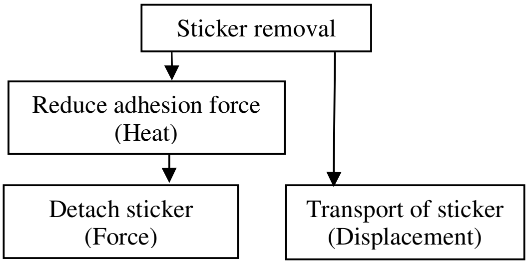

Figure 2. Function structure for toll sticker removal.

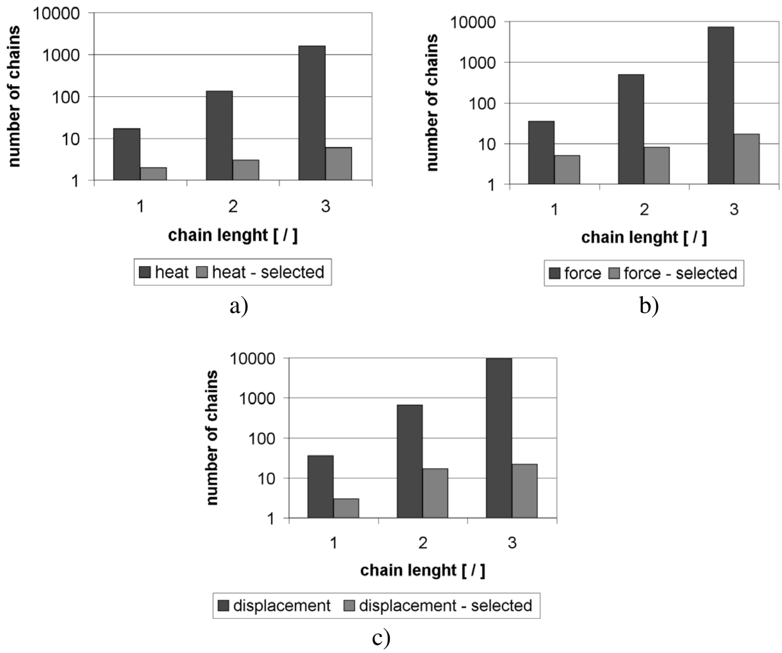

Figure 3. A number of generated and selected conceptual solutions a) for the heat as the output effect, b) for the force as the output effect and c) for the displacement as the output effect.

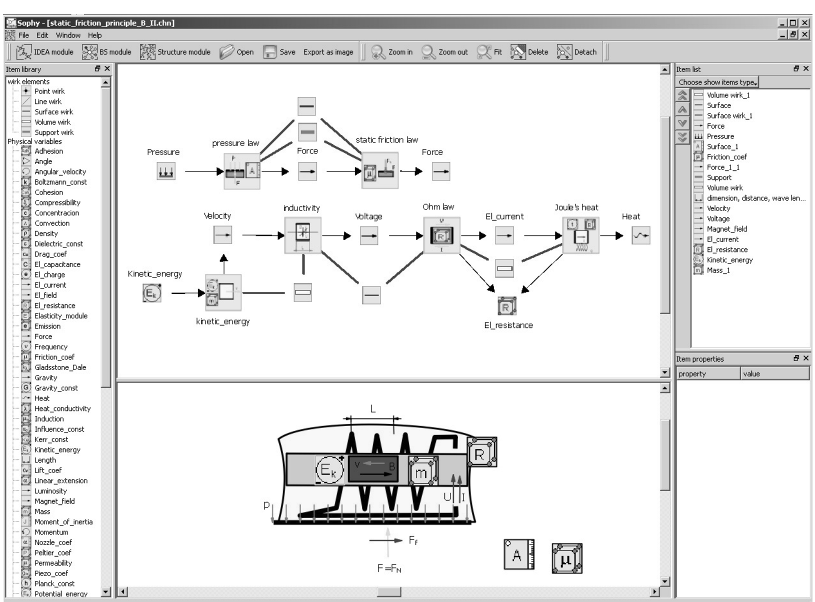

Figure 4. Map of connections between basic schemata (top), which represents conceptual system for windshield sticker removal that works on basis of static friction (top) and its embodiment (bottom).

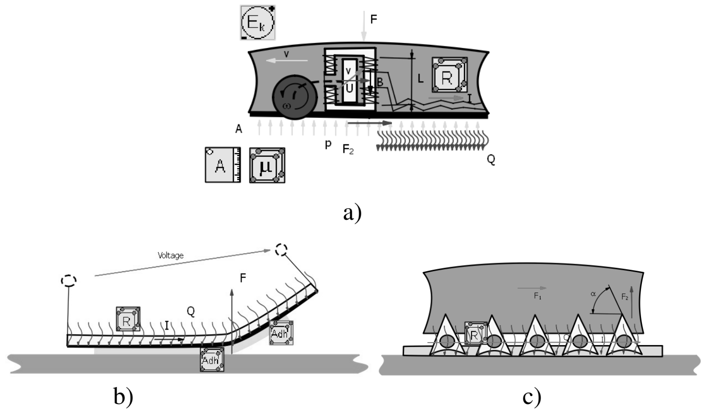

Figure 5. Embodiments of conceptual technical systems for windshield sticker removal, which were generated by chaining of physical laws.

In the structure synthesis module we imported solution chain of basic schemata for every effect (Figure 4 - top). We searched for common physical quantities and wirk elements among basic schemata. If physical quantities and wirk elements are compatible than two or more basic schemata can share them. By connecting common physical quantities and wirk elements the structural map of the conceptual technical system is generated. In the next step we proceed with structural embodiment of the technical system.

Structural embodiment starts by dragging the basic schema into structural synthesis design space where all physical quantities and wirk elements are activated. At this stage the wirk elements are merged and shaped manually, but the relations between them must remain as indicated by a basic schema (Figure4 — bottom). Nevertheless, the experiences show that the tool enables diverse embodiments of the conceptual technical system although the same chain of physical laws and basic schemata is used [5].

On the Figure 4 and the Figure 5a two different embodiments of the same working principle (the same chains of physical laws) are presented and on the Figures 5b and 5c two conceptual embodiments of different working principles are presented. All working principles were generated automatically by the computer tool called Sophy (**S**ynthesis **O**f **PHY**sical laws). The computer tool Sophy is a result of PhD research and can be downloaded from *http://www.lecad.fs.uni-lj.si/research/theory/phlaw_chains/software* under GNU general public license conditions.

6. CONCLUSION

We have described a method which automatically generates conceptual technical systems using physical laws and supports their structural embodiments using basic schemata. 19988 solutions were automatically generated for the three sub-functions of the case presented; 83 of them were selected by a design engineer as promising. Based on the selected solutions different structural embodiments of conceptual technical system were further developed. Although the conceptual ideas were automatically generated the time spent for the selection of conceptual solutions presents 60% of the whole project time and the rest was spent for the embodiment of the concepts. Since not all the selected concepts are equally good (smaller degree of functionality or due to side effects) the evaluation is one of the most important steps in the conceptual development phase. We believe that successful evaluation procedures of automatically generated conceptual technical systems will be one of the most important issues for the future development of tools to support a design engineer in concept development phase.

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