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FROM FUNCTION TO FORM USING PHYSICAL REASONING

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1. Introduction

The goal of engineering design is to design a product, which fulfils a required function. Based on a formulation of the required function the engineering designer has to determine the characteristics of the product being synthesised. The core activity in this process is the engineering designer's reasoning from statements on function to statements on the product's structure and form. This kind of reasoning is known as functional reasoning.

Due to the fact that all technical artefacts function according to physical laws, the engineering designer's knowledge about the physical laws becomes an important element in synthesis. Functional reasoning based on the engineering designer's knowledge about physical laws is known as physical reasoning. The aim of the paper is to link physical reasoning to an artefact theory, viz. the domain theory. According to this theory an artefact to be synthesised can be seen from three viewpoints or domains, viz. a transformation-, an organ-, and a part domain. Thus, the domain theory offers three types of mental objects to the engineering designer when he/she carries out functional reasoning. In the paper we describe physical reasoning seen in the light of the domain theory.

The structure of the paper is the following. In section 2 we describe a number of contributions towards explaining functional reasoning found in the literature. In the section 3 we describe the key concepts of the domain theory, the chaining of physical laws and the framework of how to carry out reasoning from function to form. In the central section 4 we discuss physical reasoning in more detail, in 4.1 we identify ways of physical reasoning and support for some of the mental operations, and describe a number of approaches to carry out physical reasoning. In section 4.2 the concept of "twisting of knowledge" is proposed to explain the engineering designer's mental operation of manipulating physics to achieve new functions. In section 5 we conclude.

2. Related work

For the German researchers (e.g. [Koller 1994]) functional reasoning is one of the main approaches to synthesise design solutions. Functional structure(s) of a technical system to be designed are defined in advance based on the engineering designer's understanding of the problem and appropriate physical effects are then searched for in catalogues to realise functions. The resulting principal solutions depend on the synthesised functional structures.

We might say that Altshuller's approach [Altshuller 1986] is in general similar to the approaches of the 'German School', but Altschuller's interest in physical laws is more that of finding laws to solve a contradiction or an obstacle embedded in the realisation of the design. A schematic (i.e. a minimal technical system) has to be generated first, followed by search for physical laws. The generation of these schematics is supported by various rules, but their application rests on experience of a design

engineer.
In Hubka's approach [Hubka 1984], function structure is not given in advance, but it grows successively, taking into account the previously chosen means (according to Function/Means law). This fact is the key difference in comparison to work of German researchers. The function structures set in advance are in contradiction with Function/Means law.
The approaches of Chakrabarti [Chakrabarti et al. 1997] and Finkelstein [Finkelstein et al. 1998] are applied in sensor/instrumentation designing and seem quite similar. Both use principle of causality where output from a 'unit' (i.e. device, transition) is input to the next. Chakrabarti represents principal solutions as strings of elementary devices, while Finkelstein represents them as sequence of physical laws.
Ulrich and Seering [Ulrich&Seering 1989] present an approach to designing single-input single-output dynamic systems that can be described as networks of lumped-parameter idealised elements, e.g. mass spring, damper etc. One of the interesting characteristics of this approach is decoupling of functional and physical issues, which might have a distant analogy to organ and part concepts of the domain theory [Andreasen 1980].
From our study of the literature we observe that the described approaches differ mainly in the ways the physical laws are introduced into design process.

3. Framework of the approaches to synthesis

In the previous section we have concluded that physical laws are a very important ingredient of synthesis. In this section we will establish a model of synthesis based on functional reasoning. We will briefly describe the Domain theory [Hansen&Andreasen 2001] and chaining of physical laws (way to synthesise solutions) [Žavbi&Duhovnik 2001], since we believe that they offer a possibility to propose a framework of how to carry out functional reasoning.

3.1 The Domain Theory

The Domain theory is an artefact theory which is unique in the sense that it explains overall purpose (required transformation) via entities carrying functionality (i.e. organs) to details (parts' form, dimensions, material, surface quality and tolerance).

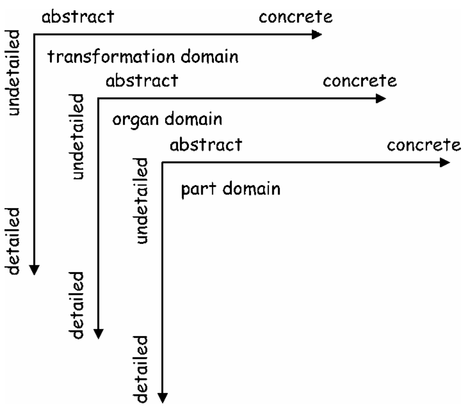

Figure 1. Three domains according to the Domain theory

According to the Domain theory an artefact to be designed is seen in three domains (Figure 1):

- a transformation domain, where focus is on the purpose oriented transformation of operands (i.e. material, energy, data), that occur when operator(s) and artefact cooperate;
- an organ domain, where focus is on an artefact's active elements (i.e. organs), that create effects, and their mode of action;
- a part domain, where focus is on allocation of the organs onto parts, that can be manufactured and assembled.

Organs (also function carriers) are active elements that create required effects in an artefact. Mode of action of an organ (i.e. the way it functions) is based on physical law(s). So, the mode of action describes the way in which the inputs to a technical system are transformed into its outputs (i.e. effects). Thus, the domain theory proposes a set of mental objects available to the engineering designer.

3.2 Chaining of physical laws

Chaining of physical laws is one way of synthesising solutions. The concept of use of physical laws is based on the fact that all technical systems function according to physical laws. The principle of chaining is illustrated in Figure 2.

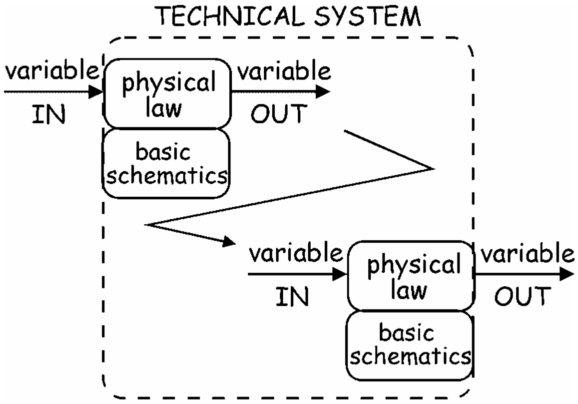

Figure 2. Chaining of physical laws and their complementary basic schematics via binding variables

Approach of chaining is based on an idea of binding physical laws and their complementary basic schematics (i.e. highly abstract organs) via binding variables. Chaining is based on the observation that many technical systems contain a chain of physical effects. A binding variable is a variable common to a physical law and its successor in a chain. The result of chaining is a chain, which describes transformation of input variable into output variable (i.e. abstract description of mode of action). The chaining is regarded as a search for and a synthesis of basic schematics into structures, which are capable to realise required function.
Existence of relation between a physical effect and a structure basically enables use of physical effects in designing.

3.3 The model of synthesis

The framework links the stepwise determination of the artifact's characteristics during the design process to different ways of carrying out functional reasoning found in the literature (see section 2). The model proposes a set of mental objects and operations needed to carry out functional reasoning.
The proposed framework consists of mental objects and operations between them. They are described as follows [Hansen&Žavbi 2002]:

- Pr (Problem): A design problem which is based on a perception of a need;
- F (Function): function, i.e. a thought, idea or intention to design something or a more chrystalised statement about the action behaviour of the product to be designed. F is not just a functional aspect of a product, but the main function, which makes the product purposeful and gives raison d'être. F may be expressed verbally as an effect: 'create heat' and may be related to an object: 'make arm to move';
- D (Design): design, which may be specified as a model of the parts to be produced and their assembly process;
- S (Structure): structure, i.e. imagination or a model of an organ structure, which carries the functionality F. The structure may be (more or less concrete and detailed) specified by its organ relations and organ characteristics, for instance as a product model;
- P (Physics): the view upon a design or structure, which explains the physical effect realising functions. The physical effect may be represented by a physical law or by models, e.g.

schematics or equations. A physical effect is either expected, Pe, to realise the required function or it is a predicted physical behaviour, Ps, of a structure or design.

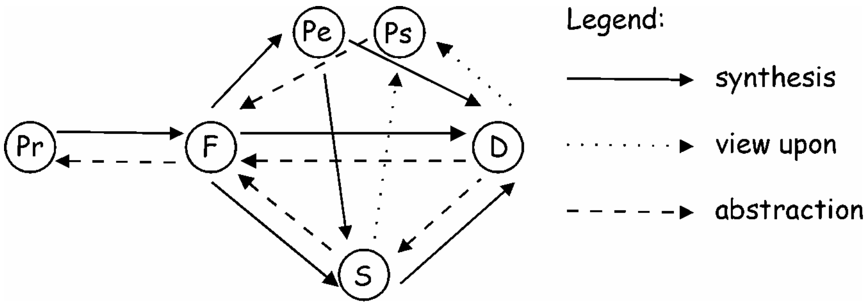

Figure 4. Framework

Between these mental objects we propose three types of mental operations related to synthesis:

- Carrying out a synthesis step, e.g. Pr → F or F → S or S → D;
- Creating a view upon the structure or design, e.g. S → P or D → P;
- Making an abstraction (e.g. of a design into its structure); e.g. D → S or S → F or F → Pr.

The set of identified objects and operations leads to the framework of synthesis shown in Figure 4. The framework can be also seen as a map which shows how and where to go from a start, e.g. from a required function, to a final position, e.g. product structure and form.

4. Physical reasoning

Among the ways from function to form that can be identified in the framework, the physical reasoning can be identified, too. All the patterns which contain Physics (P) are members of physical reasoning. The engineering designer's knowledge about physical laws is the central element of functional reasoning. The patterns Pr→F→P→S→D, Pr→F→P→D, F→P→D, F→P→S→D are all valid for function to form synthesis.

4.1 Approaches to physical reasoning

The pattern Pr→F→P→S→D represents 'full-size' product design path where the product is developed from scratch; from identified Problem (Pr) to Design (D) via Function (F), Physics (P) and complementary Structure (S). The pattern F→P→S→D is almost the same with a Function (F) of a product already known at the start. The patterns Pr→F→P→D and F→P→D differ from the previous two only in Structure (S) which is not a part of the patterns. This means that the Design (D) is reached from Problem (Pr)/Function (F) only via Physics (P).

From the study of the literature we can find support for some of the mental operations: the operation F→P is supported by chaining of physical laws and the operation P→S is supported by basic schematics complementary to physical laws. There is a great possibility that the concept of allocation of organs to parts [Hansen&Andreasen 2001] could support the operation S→D.

4.2 Twisting of knowledge

We would also like to present an activity, which can be identified in the framework and is hidden in the P→F relation. It is called 'knowledge twisting' as proposed by Andreasen. Knowledge twisting is a kind of manipulation of a Physics P (as a mental object) in order to achieve new Function(s) F. The basic characteristic of knowledge twisting is that the physical law remains the same regardless the function it fulfils. Knowledge twisting is a synthesis activity.

One type of knowledge twisting is supported by variation of physical law's independent/dependent parameters (i.e. variation assigns (in)dependency to different parameters while others are kept constant quantities) which reallocates receptor/effector wirk elements in a complementary organ and enables fulfilment of new functions. But it has to be kept in mind that all variations are physically not possible within a single physical law. Figure 5 and Table 1 illustrate an example of such variation.

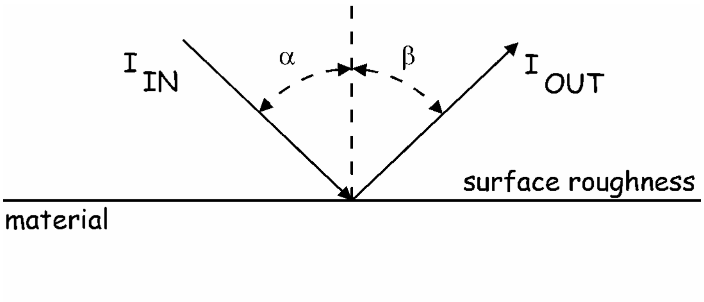

Figure 5. Light reflection: $I_{OUT} = f(I_{IN}, \alpha, \beta$, material, surface roughness).

Table 1. Variation of physical law's independent/dependent parameters (I_{IN} – intensity of incoming light ray, I_{OUT} - intensity of outgoing light ray)

Stimulus (independent variable)	Response (dependent variable)	Constant	Remark
I_{IN}	I_{OUT}	*α, β, material, surface roughness*	*e.g. 'detect light'*
material	I_{OUT}	*I_{IN}, α, β, surface roughness*	*e.g. 'detect type of material'*
surface roughness	I_{OUT}	*I_{IN}, α, β, material*	*e.g. 'detect dust'*
α	I_{OUT}	*I_{IN}, β, material, surface roughness*	*e.g. 'allow around the corner view'*
I_{IN}	*surface roughness*	*α, β, material, I_{OUT}*	*not possible*
I_{IN}	*material*	*α, β, surface roughness, I_{OUT}*	*not possible*
etc.	*etc.*	*etc.*	

When we identify surface as a stimulus, we mean that change in surface roughness affects the intensity of outgoing light ray. This combination can be used for fulfilling a function, e.g. 'detect dust.' Combination α (i.e. stimulus) and β (i.e. response) can be used for fulfilling a function, e.g. 'allow around the corner view.' In both cases the law governing the behaviour is light reflection law. And when we say that surface cannot be a response to light intensity as a stimulus, we mean that the surface cannot be affected by it, at least according to the light reflection law. Of course, light (e.g. laser light) affects surface (e.g. laser engraving) but the physical law describing the behaviour is not light reflection.

Piezo electricity is another example of how simple knowledge twisting can be carried out. One can stimulate piezo electric material with voltage and force is generated, but it is also possible to stimulate the material with a force and voltage is generated. A physical law that describes the phenomenon (i.e. both behaviours) is the same and so is its complementary organ.

The other part (assumed as the major part of knowledge twisting) seems more of creative nature and still lacks support.

5. Conclusion

In this paper we have related physical reasoning to the domain theory. Physical reasoning as a means to synthesise technical artefacts is based on the engineering designer's knowledge about physical laws and his/her ability to "twist" this knowledge into suitable design solutions. The domain theory offers a set of mental objects available to the engineering designer when he/she synthesises technical artefacts.

By relating physical reasoning to the domain theory we have proposed a framework of approaches where each step of synthesis gives concretisation and detailing of an artefact being synthesised, and where physical reasoning (in the form of chaining of physical laws) is the prime mover for synthesising solutions. We believe that the framework proposed is a contribution to sharpening of design theory, and that it has prescriptive power of how to carry through the key-step of synthesis, namely reasoning from function to form.

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