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HANDLING UNDESIRED FUNCTIONS DURING CONCEPTUAL DESIGN - A STATE - AND STATE - TRANSITION - BASED APPROACH

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1. Introduction

The majority of product faults are caused early, during conceptual design, but detected late, during product production or product use. According to the *rule of ten* and assuming that the correction of a product fault during conceptual design costs e.g. 1 EUR, then the correction of the same fault during production planning would cost 10 EUR, during production 100 EUR, and during product use 1000 EUR [Ehrlenspiel 2003]. Product faults are caused by product internal or external disturbing factors and cannot be completely avoided. Product internal disturbing factors have their origins in the physical occurrences of the technical system, whereas external disturbing factors, e.g. dust or humidity, stem from the system environment. If not identified in time and eliminated, they may lead to product malfunction or even failure. Analyses of the design process have shown, that design faults are mainly caused by insufficient clarification of the design task and inadequate search for and selection of design solutions [Ehrlenspiel 2003]. These shortcomings are, among other things, a direct result of inexistent, insufficient or inadequate methodological support in identification and processing of disturbing factors during conceptual design. The next subsection gives an overview of the state of the art in methods for identifying and processing potential disturbing factors and faults during product design.

1.1. State of the Art

Several methods aim at supporting the designer in anticipating potential product failures during design in a systematic way and suggest remedies and preventive measures. The most important are the analysis of former failure cases, the Fault Tree Analysis, the Failure Mode and Effect Analysis (FMEA), the Hazard and Operability Studies (HazOpS) and the Anticipatory Failure Determination (AFD).
With the aid of the *Fault-Tree-Analysis*, designers can seek out the possible faults or disturbances, that would cause functional failure by negating the functions of the function structure one by one, i.e. by assuming them to be unfulfilled [Pahl 2001]. *Failure Mode and Effect Analysis (FMEA)* is a formalised, analytical method for the systematic identification of possible failures and the estimation of related effects. The main goal is to avoid or limit risk. Thereby, possible failures are determined together with their causes, consequences, risk numbers, and test and remedial measures are suggested [Pahl 2001]. The technique *Hazard and Operability Studies (HasOpS)* is used for identifying potential hazards or operability problems caused by deviations from the design intent of new and existing process plants. Goal is to review the plant in a series of meetings, during which a multidisciplinary team methodically *brainstorms* the plant design The success of HazOpS depends mainly on the completeness of the data used as a basis for the study, the technical skills and insights of the team and

the ability of the team to use the approach as an aid to their imagination in vizualizing deviations, causes and consequences [Lihou]. The methods presented so far have in common, that the process of failure prediction proceeds linearly from an articulation of the technical system's functions to what may occur if there is a failure or an absence in deliverance of these functions. The analytical line of logic follows the design intent. One drawback of the methods stems from the process used to determine failures which is essentially a brainstorming exercise, initiated by probing what failures might occur. *Anticipatory Failure Determination (AFD)* is a TRIZ method by which the user can thoroughly analyze given failure mechanisms, obtain an exhaustive set of potential failure scenarios and develop inventive solutions to prevent, counteract, or minimize the impact of the failure scenarios. The approach to determining potential failures is the reverse of the one used in conventional approaches such as FMEA or HazOpS. The idea is to invent, cause and create failures [Crow 2002]. At the present time, however, there is no process-oriented and knowledge-based approach, that systematically supports failure anticipation by considering implicit functions realized by principle solutions as potential failure causes, making them explicit and processing them.

Goal of this paper is to present a concept that supports the designer in handling undesired functions during conceptual design in a systematic way. Undesired functions originate from properties inherent to principle solutions and fulfill them, but are not desired for the design task considered, because of their potential intolerable disturbing impact on the future product and / or on its environment. By making explicit such information and offering methodological aid in handling it, the designer is supported in identification and processing of internal disturbing factors, which constitute potential causes of product malfunction or failure (section 2). With regard to a computer support, the nondeterministic process of handling undesired functions, a subprocess of designing, is described by its states and the according state transitions. For the knowledge representation, a solution patterns approach, with object patterns and process patterns, was adopted. The concept is verified with a product example (section 3).

2. Methods

This section presents the foundations, on which the presented concept bases, followed by considerations about identifying and processing undesired functions inherent to principle solutions.

2.1 Foundations

Widely the terms *behaviour* and *function* are used to describe the input-output-relations of a technical system. Hereby the term behaviour describes the whole amount of input-output relations of a technical system, whereas functions are specified only as the desired ones.

In the context of this paper the term *function* is defined as the general input/output relationship of a technical system, whose purpose is to perform a task [Pahl 2001]. After establishing the function structure of a technical system, the solutions to the sub-functions are elaborated. Sub-functions are usually fulfilled by physical, chemical or biological processes. A physical process, realized by the selected physical effects, the working geometry (arrangement of the working surfaces and working motions) and the material, results in a *working principle* that fulfils the function in accordance with the design task. To satisfy a function, the working principles of the sub-functions of the function structure are combined into the *principle solution*.

In general, not every function performed by a technical system is intended. Thus, functions of technical systems can be subdivided into *intended functions* and *unintended functions*. In the context of this paper, those unintended functions, originating from principle solutions, which can cause product malfunction or even failure, are referred to as *undesired functions* [Langlotz 2000]. Generally, undesired functions are not only caused by the nature of principle solutions. Also geometry, tolerances, materials, lubricants, effects of production processes like hardening or surface effects might cause undesired functions. In the context of this paper, however, only the undesired functions caused by the nature of principle solutions are considered.

2.2 Identifying unintended functions

During designing, the intended product functions are fulfilled by selection of appropriate principle solutions. In general, and as a result of inherent properties, principle solutions perform, in addition to the intended functions, for which they were selected, additional functions. Analyses of various types of principle solutions have shown, that inherent unintended functions can manifest themselves as disturbing factors either by *reducing the input of an intended (sub-)function* or by *producing an undesired output* (Figure 1).

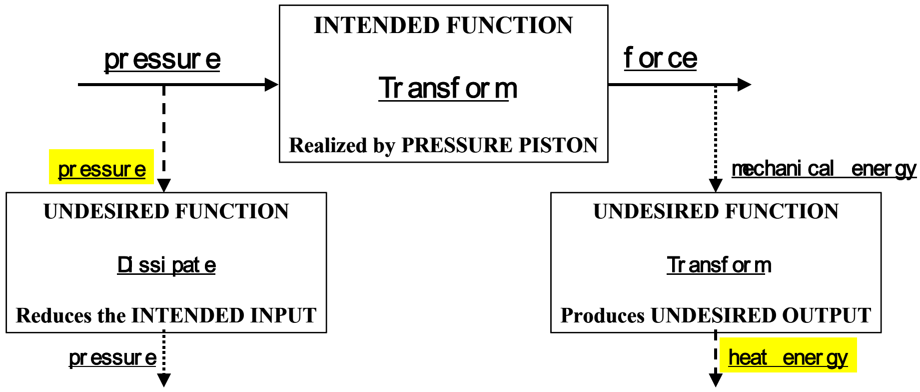

Figure 1. Types of unintended functions originating from principle solutions

For example, to fulfill the intended (sub-)function *transform pressure into force*, the principle solution *pressure piston* is selected. The analysis of the pressure piston revealed the inherent properties *friction between piston and cylinder* and *pressure loss*, from which the unintended functions *transform mechanical energy into heat energy* (which produces an undesired output), and *dissipate pressure* (which reduces the intended input) respectively can be abstracted.

Unintended functions, inherent to a selected principle solution, constitute potential disturbing factors for the future product and its environment. Therefore, they have to be identified, when selecting a principle solution and processed if they show an intolerable disturbing impact on the future product and its environment. The next subsection presents considerations about processing undesired functions.

2.3 Processing undesired functions

After identifying unintended functions, originating from principle solutions, their effects on the product and on the product environment have to be anticipated.

The *disturbing impact of an unintended function on the product* is estimated by considering the internal product environment. Assuming, that a product is made up of a number of components and that each unintended function originates from (at least) one component, then the remaining product components constitute the internal product environment for the component under consideration. During conceptual design, the internal product environment is defined by the function and principle solution structures of the components, and a tentative spatial arrangement of the components. The embodiment is not yet determined at this stage. Hence, the compatibility of the function structures and the principle solution structures, together with the spatial arrangement of the components in the design working space, decide about the disturbing impact of an unintended function on the product itself. For example, if a heat producing component is placed close to a heat sensitive component, then the heat producing component may have a disturbing impact on the functionality of the heat sensitive component. The spatial arrangement of the neighboring components is not compatible.The unintended function *produce heat energy* of the heat generating component is undesired and has to be processed.

The *disturbing impact of an unintended function on the product environment* is estimated by considering the external product environment. It describes the product environment by requirements, the relations among them and to the product.

If we consider, for example, a *coal-fired steam power station*, then the function *generate fumes* is unintended. The fumes of a coal-fired power station contain a high sulphur concentration. If the steam

power station is employed in a country with a determinate limit in sulphur concentration of the fumes, and produces a higher sulphur concentration than permitted, then the function *generate fumes* is undesired and has to be processed. On the other hand, in countries without determined limits for sulphur concentration of fumes, the unintended function *generate fumes* does not need further consideration.
The disturbing impact of undesired functions on the product itself can often be reduced to a tolerable measure or eliminated by changing the internal product environment, either by rearranging it or by replacing the disturbing and/or the disturbed component. The external product environment however is not as easy to modify.
Figure 2 depicts the different types of counteractive measures, which can be employed to process undesired functions with disturbing impact on the product and / or on its environment.

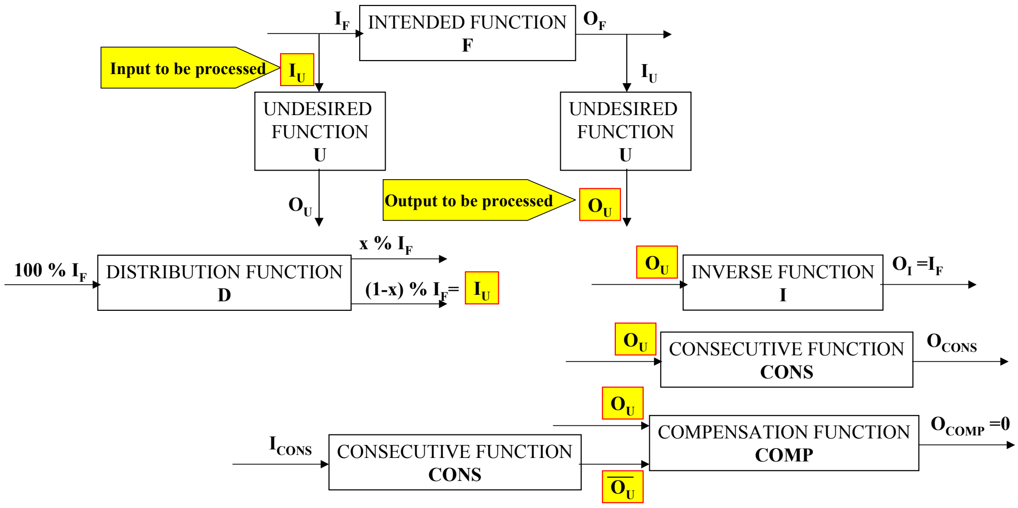

Figure 2. Processing undesired functions

According to the classification of undesired functions *U* into functions that *reduce the input of an intended function F* and functions that *produce an undesired output,* the counteractive measures are the *reduction of the input of the undesired function* I_U and the *reduction of the output of the undesired function* O_U respectively. In the following subsections, the counteractive measures will be presented and exemplified.

2.3.1 Reduction of the input of an undesired function

Assuming, that a fraction of the input of the intended function is used as input of the undesired function and hence reduces the input of the intended function, there must exist a distribution function (*D* in figure 2) of the undesired function, which has to be identified and optimized. However, it is often difficult or impossible to localize or determine the distribution of the undesired function.

2.3.2 Reduction of the output of the undesired function

The output of an undesired function, O_U, can be reduced in three ways (figure2): with the aid of an *inverse function, I*, a *consecutive function, CONS,* or a *compensation function, COMP*.
An *inverse function* in serial connection to the undesired function, transforms the output of the undesired function back into the input of the intended function. For example, a catalytic converter transforms the exhaust gases of an internal combustion engine, so that the undesired function *transform fuel into exhaust gases* is eliminated. However, the technical realisation of an inverse function is often difficult or impossible.
A *consecutive function* in serial connection to the undesired function, transforms the output of the undesired function into a tolerable amount. For example, by employing a cooling system, the heat dissipation caused by an internal combustion engine is reduced to a tolerable limit. A consecutive function is applied when an inverse function is difficult or impossible to realize.

If the output of an undesired function cannot be connected directly to an inverse or a consecutive function (for example, in the case of noise generation of a passenger car), then a complementary output (for example vibrations in paraphase) to the undesired output has to be produced with the aid of a consecutive function. The output of the consecutive function and the undesired output are then superposed in a *compensation function* and the undesired output thus compensated.

3. Results

In this section, a model of the *generic process of handling undesired functions, caused by the nature of principle solutions*, is presented and verified with the principle solution *pressure piston*. It was found, that *handling undesired functions caused by the nature of principle solutions* is a nondeterministic subprocess of designing, characterized by a high degree of uncertainty and a high decision making intensity. In order to realistically model it with regard to a future computer support, the process of handling undesired functions was described by its states and the corresponding state transitions. According to [Leutsch 2003], and because engineers think in cases during problem solving, for the representation of the declarative and procedural design knowledge, the approach of adaptable and reusable object patterns and process patterns respectively was adopted. An *object pattern* is the formal specification of the static knowledge of handling undesired functions and directly supports the process by allocating a process state *Si* to its subsequent state *Si+1*. A *process pattern* is the formal specification of the dynamic knowledge of handling undesired functions and directly supports the process of handling undesired functions by allocating a state *Si* of the process to actions *A*, that lead to the subsequent state *Si+1*.

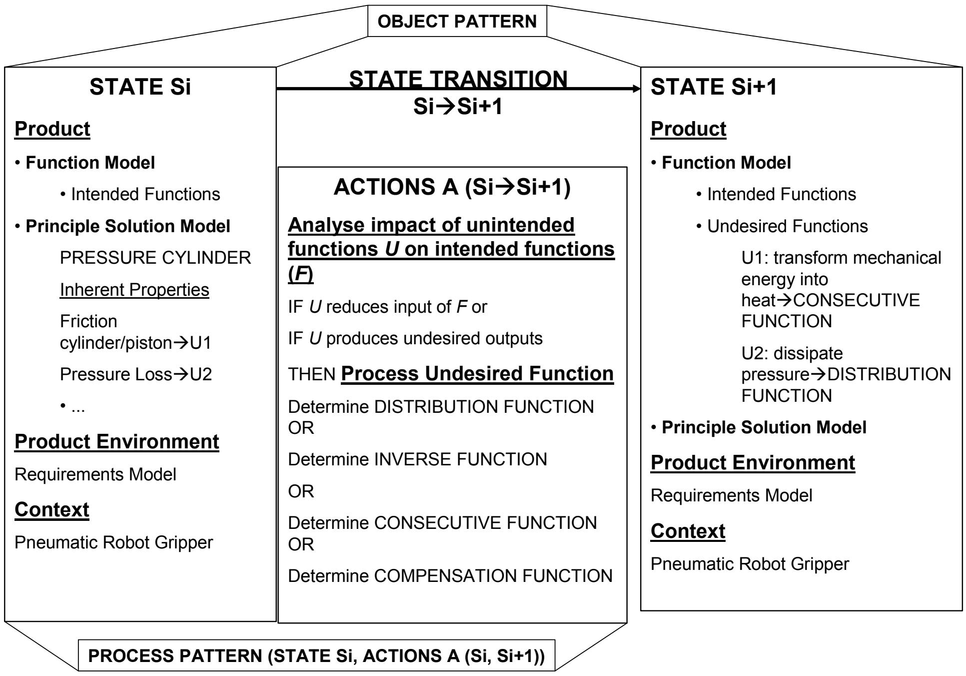

Figure 3. Relationship between a state transition and object and process patterns

In figure 3, the relationship between two subsequent states and the corresponding state transition on the one hand, and an object pattern and a process pattern on the other hand, is depicted for the undesired functions of a *pressure cylinder*. A state is generally specified by the actual product model, the product environment model and the context of the design task. In the *pressure cylinder* example, the inherent properties *friction between cylinder and piston* and *pressure loss* cause the unintended functions *transform mechanical energy into heat (U1)* and *dissipate pressure (U2)*. The set of actions represented in figure 3 support the state transition to the subsequent state *Si+1* by analysing the impact of the unintended functions on the product and on its environment, and in case that the unintended functions are undesired, by processing them. In the presented example, the undesired function *transform mechanical energy into heat* can be processed by determining a consecutive function for it, whereas the undesired function *dissipate pressure* can can be processed by determining and optimizing its distribution function.

4. Conclusions

This paper addresses the problem of failure anticipation during conceptual design. By introducing the concept of *undesired functions originating from principle solutions*, it outlines the importance of regarding properties inherent to principle solutions as a frequent cause of product malfunction or even failure. Thus, product fault causes, originating from principle solutions can be identified and processed at the earliest point in time possible, during selection of principle solutions. Two types of undesired functions, those reducing the intended input and those producing an undesired output, are identified. According to this subdivision, undesired functions can be processed either by determining and optimizing their distribution function or by finding inverse, consecutive or compensation functions to them. With regard to a future computer support, the nondeterministic process of handling undesired functions was modelled by its states and the according state transitions. For the representation of the declarative and the procedural knowledge, object patterns and process patterns were employed.

Being able to anticipate and process faults caused by the nature of principle solutions during conceptual design in a systematic way will improve product quality and at the same time reduce development time and costs. By storing the design expertise in reusable and adaptable object patterns and process patterns, the approach will support new designs as well as redesigns.

The concept presented in this paper is a first step towards an ontology-based metamodel for handling undesired functions stemming from principle solutions, as a basis for an intelligent failure anticipation system. The concepts of identifying and processing undesired functions will be further elaborated. More research has to be done in assessing the disturbing impact of undesired functions on the product and on its environment and in decision making under uncertainty. This implies further studies of the complex cause-effect relations of product faults. Generic failure scenarios, caused by undesired functions, will be abstracted. Ontologies of causes and effects, as a basis of a common vocabulary for interdisciplinary product design have to be developed.

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