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THE RELATIONSHIP BETWEEN FUNCTIONS AND REQUIREMENTS FOR AN IMPROVED DETECTION OF COMPONENT LINKAGES

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1. Introduction

Managing and predicting change in complex design is an essential task and can make the difference between developing a product on time and within budget and failing to deliver at all. Recent research into change prediction has looked at ways to improve the abstract product models that are used for change prediction by considering functional relations as well as other linkage types between components [Keller et al., 2007].
Models are a vital part of human cognition. Without internal (mental) and external (e.g. CAD or sketched) models, engineers cannot reduce the complexity of design problems. Abstract models are a means of simplifying reality and seeing familiar problems in a different light to come up with creative ideas. The properties of a model define the operations that the model affords, thus the way models are built biases what can be done with the models.
Product models in design are used to represent product information and can be used for different tasks. Product models are typically simplifications which highlight only the aspects that are important to perform a certain task successfully and efficiently. For example, a 2D-drawing of a product contains geometrical data in order to support manufacturing or dimensional integrity, while a product model in terms of a parts list contains information about product parts, such as materials, quantities, etc. Product function models – which are used in very early stages of the design process – are used to develop and depict the functions that the product needs to provide. Functional product models store the information about how a product works and how it interacts with the environment (i.e. users, adjacent systems, etc.). In order to derive the functions of a product systematically and to relate them to each other, hierarchical structures – so called function trees – can be used. These function trees are based on the assumption that each function can be broken down into sub-functions in a clear and well-defined way, although in reality it is not as easy as suggested – sub-functions can contribute to more than one upper function and cannot be clearly assigned to a single upper function any more. Such a functional breakdown generates a function lattice rather than a function tree [Simon, 1969].
Many methods in engineering design rely on abstract functional models. The main problem with many of these methods is that they can be very sensitive to the quality of the input information and that “overlooked” relations can bias the results obtained by analysing the models; in the worst case, analyses performed with these models give wrong or even counterproductive results. Therefore considering as many functional relations as possible is crucial for building functional models.
Traditional approaches such as Pahl and Beitz [1996] advocate a hierarchical breakdown of the key function of the product, but do not fully consider all life stages of a product. This paper describes a

method that extends traditional function elicitation methods using a “whole life” perspective which leads to a more complete functional breakdown of the product (Section 2). The main argument is that depending on its life stage, the key function of a product is different, leading to different function breakdowns. As an example application we use the development of a change prediction model (Section 3) of a humanoid robot (Section 4) to show how the method described here leads to more complete product models.

2. Defining the relationship between requirements and functions

In order to support building functional product models, a systematic way to build function trees is needed. As soon as the main function is identified, it can be used as starting point for the intended breakdown and the sub-functions will be derived in a structured way. The challenge is to find suitable starting points for functional breakdowns (see for example [Pahl and Beitz, 1996]). However, even if this is addressed, current methods do not capture the full range of functions that products fulfil through their life from manufacturing to disposal, so additional functions need to be identified.

2.1 Example: Ballpoint-pen

In order to build a functional product model of a ballpoint-pen, we need to look for the main function [Pahl and Beitz, 1996] of the pen which can be expressed as: *Convert hand movement into script,* which can be broken down into the sub-functions “*Transmit movement from hand to ball*“ and “*Transfer ink from cartridge to paper*, as shown in Figure 1.

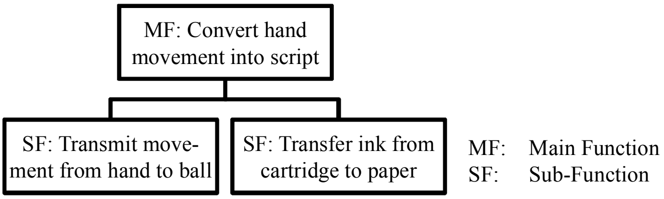

Figure 1. Function tree of ballpoint-pen

Most ballpoint pens have clips, whose functionality is not detectable if only the main function is considered. Further functional breakdown of the main function would go deeper into the hierarchical structure of the ballpoint pen and all elicited sub-functions will contribute to the main function.

As shown by this example, standard techniques to elicit the functions of products tend to “miss” some important functions as products are usually examined in the context of operation, while different stages of its life-cycle impose completely different requirements on the system. Thus, completely different functional interactions between systems and their environments exist at different times and are often neglected. Finding all these changing system requirements is not supported methodologically by current approaches.

2.2 The difficulty of conducting a systematic search of functions

The function provided by the clip is to *fix the pen to a shirt in order to transport it* is not a sub function of *convert hand movement into script* and hence cannot be subsumed in an ordinary function tree. More functions can be found that do not fit into the function tree, e.g. the function of the release mechanism that may be located at the top of the pen as well. These extra functions are not gathered systematically in hierarchical breakdowns of the main function. Thus, the approach needs to be modified to support the discovery of extra starting points for additional functional breakdowns.

Another problem with the current approach is that it targets functions rather than requirements. However, functions fundamentally exist to fulfil requirements imposed on a product. As designers are familiar with thinking about requirements, integrating requirements in functional product modelling might be a means to identify further function trees of a product.

It is clear that *convert hand movement into script* refers to a function, but the distinction between functions and requirements is not always clear cut, for example when the carrying-capabilities of the system are discussed, some might say that the transportability of the pen is a necessary feature of the system, but it does not provide a functionality that (on its own) would be an argument to sell or buy a system, like the main function *Convert hand movement into script* would be.

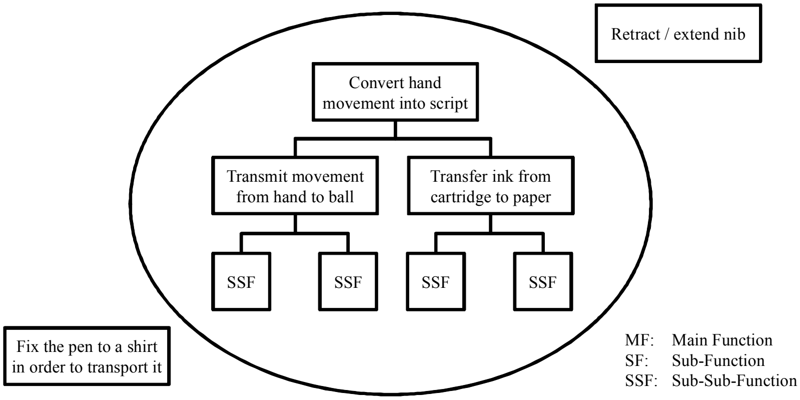

Figure 2. Not all functions are elicited by breaking down the main function

However, when the transportability of the system is considered a different function breakdown becomes necessary. In order to explore the function *transport ballpoint-pen*, the system boundary needs to be adjusted so that the user who is *retracting the nib*, *holding the pen in order to lift it* and the device which is actively *transporting the ballpoint-pen* (shirt, chain around people's neck, etc.),need to be taken into account. Thus, in order to display and actively work on those functions, additional adjacent systems (user, shirt, etc.), which actively carry out the discussed functions, but which are located outside the system boundary must be included in the model.

By accounting for the wider system, the transportability can be treated in the same way as other functions. The initial system boundary, which was chosen to display the main purpose of the system (here: to *convert movement into script*) was extended, thus the model was extended.

But if the system boundary it is kept fixed so as not to permanently extend the system boundary the transport function would not be visible as a self-contained function. Thus, the distinction of functions and requirements allows considering the transportability without extending the system boundary, which is drawn around the system in focus. The distinction thus facilitates when building functional product models.

2.3 The relationship between functions and requirements

The findings from the previous section can be transferred into a structure which captures the relationships between functions and requirements. Requirements on the system can be broken down into functions fulfilled by the system under consideration (see Figure 3). Thus the requirements are aligned higher in a hierarchical structure than the functions which contribute to meet the requirement. In the ball point pen example the requirement "being transportable" can be broken down into the functions *retract/extend nib* and *fix pen to transport device* (one level lower, Figure 3-right), which are fulfilled by the system "ballpoint pen" and thus are located inside the system in focus. The requirement "being transportable" becomes a starting point for a further functional breakdown.

Figure 3-left shows that the described way of structuring of functions and requirement is also valid if the "main function" of the ballpoint pen is regarded. Superior to the function *convert hand movement into script* the requirement of *store information* can be determined. Thus, this figure refers to a system boundary including the ballpoint pen and the medium on which the script is superimposed.

As shown with this simple example, traditional model building procedures do not explicitly give hints to examine a system in contexts apart from the operating environment, for example transportation, recycling or assembly. A good point to start from is the requirements (see Figure 3) a system has to fulfil. Each function will contribute to a certain requirement, so if the requirements are broken down, more function trees will be created and the product model elicitation process will become more structured and comprehensible.

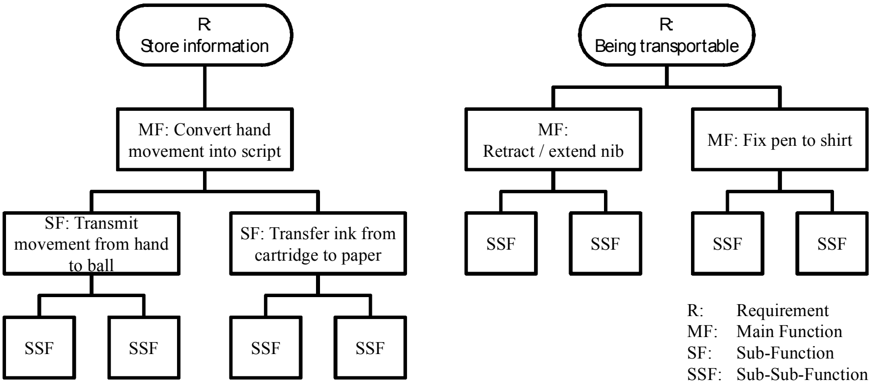

Figure 3. Functions are related through requirements which are sources of additional function trees

3. Extended functional modelling for improved change prediction

The following section shows how this theory about the relationship between functions and requirements supports a specific aspect of the design process: change management and –prediction. Generally the findings from the previous sections support the identification of relations within a product that otherwise often remain unconsidered. This identification of additional relations can enhance methods relying on a thorough functional basis such as the Change Prediction Method (CPM) used for predicting change propagation and the Contact & Channel Model (C&CM) which is used to elicit the required functional product models.

3.1 The Change Prediction Method (CPM)

Being able to predict changes in a complex product has been identified as an important problem in industry [Clarkson et al., 2004] especially when different alternative solutions for a given change request have to be analysed. The Change Prediction Method (CPM) as a solution to this problem has been successfully applied to a number of industry sectors such as aerospace and automotive [Jarratt et al., 2004]. It is based on a component-component change propagation risk mapping of a complex product and provides risk estimates of a change to one component affecting other components in the design by drawing designers' attention towards high-risk change interactions.

The method consists of a three-step process: building models in group meetings with domain experts, computing change risks between component pairs and offering a number of visual representations for visualising and analysing change risks. Like in many other methods, links between components that were "forgotten" during the model building stage can have significant effects on the results. Thus, the more structured the links are determined, the better the prediction results will be. Recent research [Keller et al., 2007] extended the model building approach towards considering functions by utilising the Contact and Channel Model (C&CM), a description of the functions involved in product operation, in the approach of eliciting more "complete" models. In this paper this issue is extended to other linkages resulting from different stages of the product life cycle.

3.2 The Contact and Channel Model (C&CM)

The core of the C&CM is a systematic function-component mapping [Matthiesen, 2002] that locates functions on components and thus makes functions visible. It provides a product model in terms of

Working Surface Pairs (WSP) and Channel and Support Structures (CSS) which are clearly defined on the abstract level of functions as well as on the concrete level of components.

The key idea of this approach is that a function of any technical system can only be fulfilled through interaction of adjacent systems (in terms of action = reaction) (Basic Hypothesis I). Thus, an effect can only be obtained if a Working Surface (WS) is in contact with another WS and thereby creates a WSP. If this idea is systematized it becomes clear that a technical function requires a further WSP and a structure (CSS) that connects both WSP (Basic Hypothesis II). A technical function is defined in terms of the input-output relation of energy, material and information [Matthiesen, 2002]. A whole system is completely describable through a structure of WSP and CSS (Basic Hypothesis III). The functions are determined by the properties of the WSP and CSS and their interconnections.

In terms of the C&CM approach, descriptions are generated for particular problems through assigning a set of Working Surface Pairs and Channel and Support Structures to a specific function and searching for solutions on this clearly assigned level. The C&CM approach then picks and groups elements of the existing description in a new way, exploring the inherent ambiguity of how elements of a description can be grouped.

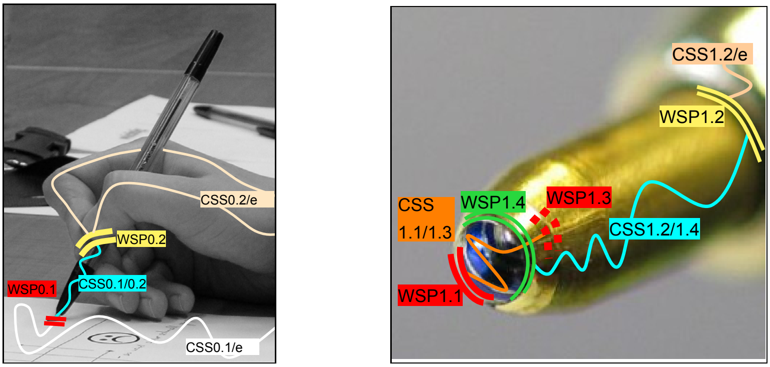

Figure 4. Functions visualized through Working Surface Pairs and Channel and Support Structure and Detailing of the description

For example the function of a ballpoint pen (see Figure 4) cannot be fulfilled unless *WSP0.1* between paper and pen, *WSP0.2* between pen and hand and the *CSS0.1/0.2* represented by the body of the pen exist. If one of these elements is not present the function cannot be fulfilled. For example if somebody tries to write on glass, WSP0.1 does not work correctly. Reasoning on a lower level of detail is required to work out why the function cannot be obtained. What effect prevents writing on glass? Is there not enough friction to turn the ball, or do the properties of the liquid ink prevent adhesion of the ink to glass? Are there other reason? As Keller et al. [2007] argue the C&CM is a useful tool to systematically elicit interrelations on the functional and component levels which might be used for change propagation path analyses in evolutionary design.

4. Example: ARMAR III humanoid robot

This section describes how the new approach of capturing additional functions in the early stages of the design process, described in section 2, is used to improve the Change Prediction Method that has been outlined in previous research [Keller et al., 2007]. This approach has been extended by considering the requirements of the whole life-cycle of the product to find and capture additional functions systematically, allowing for more complete models and better change predictions. Thus, in principle the mapping of functions onto components (and vice versa) in terms of C&CM remains the same as e.g. described in section 3.2. The difference to the former approach is the procedure of how the model is built up, i.e. how the functions of a product are elicited. Including requirements provides a more reliable guideline for C&CM product model elicitation by imposing a superstructure on the main-function/sub-function approach used up to now.

4.1 Background of the case study

The design process of the ARMAR III humanoid robot developed in the Collaborative Research Centre 588 at the University of Karlsruhe (see Figure 5 left) has the goal of creating a humanoid robot that is able to support humans in a variety of different tasks independently or in cooperation with humans. A very ambitious set of requirements has led to a design which is highly spatially and functionally integrated. The complex interactions between system elements pose further challenges in terms of predicting and handling knock-on changes. The mechanical design of the ARMAR III robot is generated by a team of 5 engineers with 2 to 5 years of experience in designing the ARMAR III and its predecessors. They are supported by several research students who generate CAD drawings and undertake Finite Element Analysis, Multi Body Simulation and Optimization tasks.

In order to predict modifications required to develop a new version of the robot neck (see Figure 5-right), an approach based on previous work, presented in [Keller et al., 2007] was used. This approach makes use of a C&CM product model which was extended through the function-requirement relationship outlined in Section 2 and then was used to predict and analyse change behaviour of the robot neck to facilitate the design process. The case study included observations of designers carrying out development tasks and 3 semi-structured interviews totalling 9 hours with system experts.

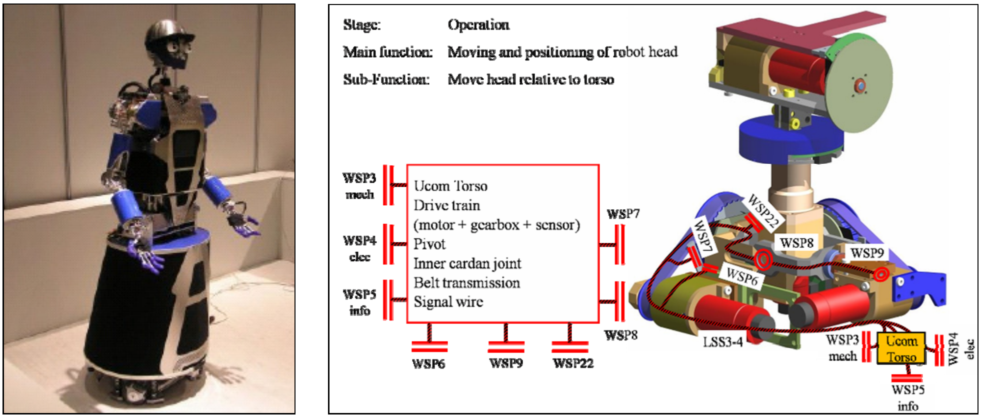

Figure 5. Humanoid robot ARMAR III and the sub-assembly "robot neck" with a function mapping according to C&CM

4.2 Results from the case study

Designers modelling certain sub-assemblies of the robot in terms of the C&CM pointed out in a previous study that not all the functions of a product were found by breaking down the main function. They mentioned the difficulty in finding these extra functions systematically and relating them to those already identified.

This problem was solved successfully by including requirements into the C&CM model and using them on the highest hierarchical level to find more functions fulfilled by the robot neck. A superstructure was determined that exhibited new starting points for further functional breakdowns and that related the single function trees to another. The structure of functions and requirements is shown in Figure 6. These functions then are located through WSP and CSS on the geometry of the robot neck (Figure 7-right) and represent for CPM relevant component linkages.

In the case study of the robot neck for example, the requirement *assembly must be possible* (compare Figure 6) was identified which led to the function *grant tool access*. Without using requirements this function would be very difficult to elicit and would not fit into the conventional function-hierarchies (how this particular function is mapped onto the product is part of current research). This is valuable with regard to change prediction (CPM), using C&CM to provide a functional basis. It is important to be able to elicit functions that are realised in a product as structured as possible, not just the obvious ones. Otherwise certain component interactions will be omitted and might lead to unexpected change propagation. Thus, for building functional product models in general and for change prediction in particular, it is of vital importance to include as much relevant information as possible in order to improve the results that are obtained by using the model.

Comparing two different CPM matrices of the robot neck, the first one using simple component-component relationships with linkage types [Jarratt et al., 2004] and the second one using the modified "requirement"-based approach, confirmed the hypothesis that a better approach for functional product modelling will lead to more comprehensive product models and to extended data bases. While the first approach elicited 90 component interactions, the modified "requirement"-based approach extracted 10 further interactions which resulted in notably higher risk values. Previously omitted component interactions were now considered and change prediction was able to deliver more complete results.

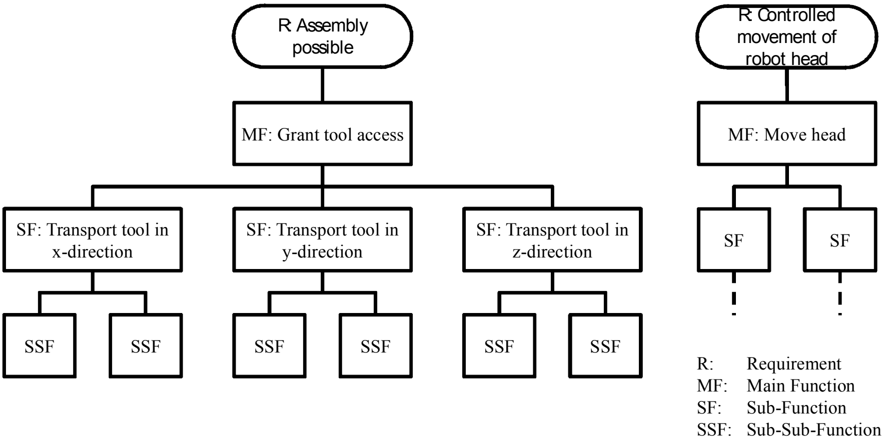

Figure 6. Extended functional breakdown by using requirements

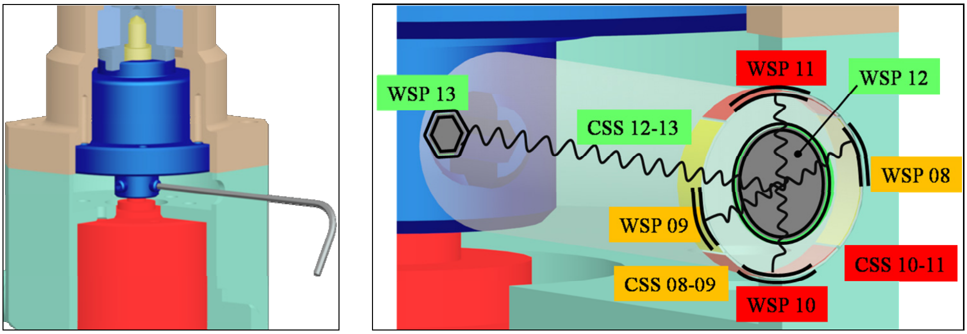

Figure 7. Linkage between components through the requirement "assembly must be possible"

5. Conclusions

The definition of the relation between functions and requirements provides a structured way of identifying component connections which are otherwise disregarded. This core result of the research project underlines the strength of functional modelling. The approach provides the basis for a directed and systematic strategy of revealing the structures hidden within a product, by facilitating the building of more complete product models. The determination of the relation of requirement and function will especially improve the model building through the Contact and Channel Model C&CM.

The case study has shown a strong need for designers to capture and document the normally disregarded component connections. This is particularly useful when the design changes quickly and product knowledge is lost as in the case of the ARMAR III humanoid robot. The increased efficiency allowed by the method is obtained at the expense of a greater effort put into building product models.

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