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SYSTEMATIC MECHATRONIC DESIGN OF A PIEZO-ELECTRIC BRAKE

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ABSTRACT

The design of mechatronic products has found rising attention in recent years ([1]-[7]). One well-known problem when designing a mechatronic product is the choice of the appropriate systematic methodology that can effectively help in guiding and organising the design process. In the German VDI guideline 2206 [8] a systematic procedure for the design of mechatronic products is proposed. This procedure is to a large extent based on the V-model for the development of electronic systems (compare e.g. Möhringer [9]). This paper describes an application of this procedure for the development of mechatronic products one the one hand in a small design process of a single designer and on the other hand in a large-scale automotive product development process. The small design process consists of the systematic development of a piezo-electric brake. This brake consists of mechanical, electrical, and electronic subsystems and thus represents a mechatronic system. The large design process is focused on the development of control systems for car engines. During both developments it became clear that the procedure described in the V-model and in the VDI 2206 needs to be accompanied by more concrete design methods. Therefore one of the most acknowledged design methodology, the "Konstruktionslehre" by Pahl & Beitz [10] was used in addition. This paper describes the experiences in the application of the V-model and presents first steps towards an innovated methodology, which could systematically organise the design process of a mechatronic product.

Keywords: V-model, VDI guideline 2206, Pahl & Beitz design methodology, piezo-electric brake, systematic design, mechatronic design methodology

1 INTRODUCTION

This paper intends to explore the application of the V-model in the product development of mechatronic products. Consequently, the V-model and its description in the VDI 2206 [8] are described in Section 2. During the analysis of two different design processes it became clear that additions are needed. For the sake of its level of detail and its worldwide distribution in product design, the design methodology by Pahl & Beitz [10] was used. This methodology is briefly described in Section 2 as well. In Section 3 the design process of an individual designer—the development of a piezo-electric brake—is described and analysed. A similar analysis of a large-scale automotive product development process is provided in Chapter 4. The analysis results are compared and summarised in Chapter 5.

2 METHODOLOGY

2.1 V-Model

The V-model is an abstract model of the system development lifecycle. It was first developed by the German federal administration to regulate a software development process in 1997. However, through some adoption and modification the V-model has been suggested by the Association of German Engineers (VDI) committee A127 as the "VDI guideline 2206: Design methodology for mechatronic systems". Figure 1 shows a general structure of the V-model as described in the VDI guideline 2206.

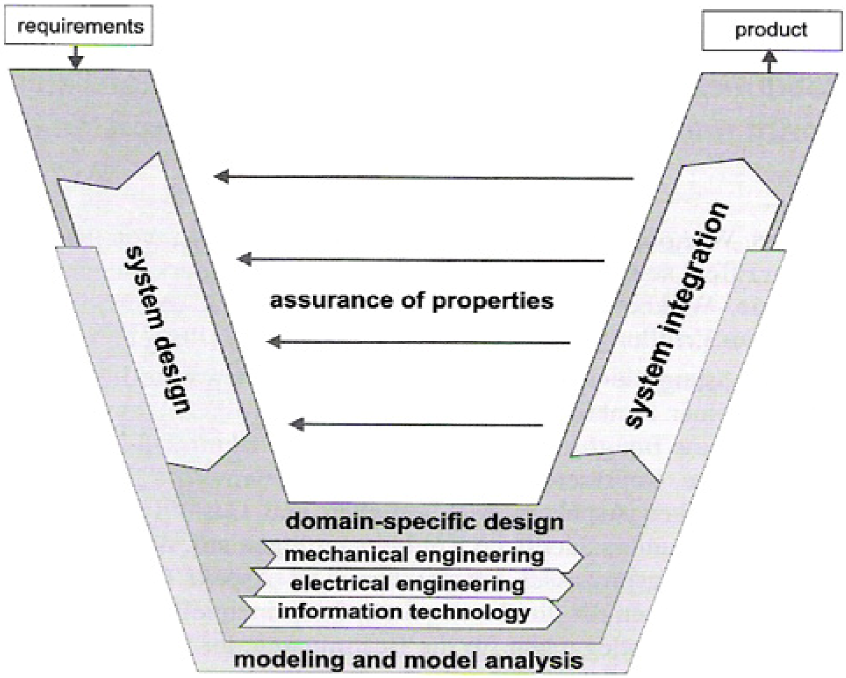

Figure 1: V-model [VDI-Guideline 2206]

In the VDI guideline 2206, the V-model is first initiated with the **requirements list** of the system. This requirements list provides the specification of the product or system, which is going to be developed, and forms the measures against which the product is to be assessed. Based on this requirements list, the cross-domain solution principle, which describes the main physical and logical operating characteristics, is established. This stage of development is called **System Design**. In this stage, the overall function of the system is divided into several sub-functions. Each sub-function is assigned to a suitable operating principle or solution. On the basis of this jointly developed solution, further concretisation takes place in the **Domain-specific Design** stage which is done separately and independently in each domain. Detailed calculations, drawings, analyses, or simulations are produced at this stage in the respective domains. In the **System Integration** stage, results from all the individual domains are integrated. Interactions between the sub-functions are taken into account for investigation as well as the verification and validation process for assurance purposes. The final result of the V-model is the **mechatronic product**.

2.2 Pahl & Beitz Design Methodology

Pahl & Beitz [10] have divided the design process of a technical system into four main phases, which can be used by the designers as a guideline. Figure 2 shows the division of the design process as well as the activities taking place in each phase. In the planning and task clarification phase, research is carried out to get some ideas about the product, which is going to be developed, through several activities like market survey, analysis from the customers' feedbacks and so on. This will lead to the formulation of a requirements list. In the conceptual design phase, the principle solution for the problems relating to the product requirements will be determined. This is done by abstracting the essential problems, establishing function structures, searching for suitable working principles, and combining those principles into a working structure. The next task is the embodiment design phase. During this phase, designers start with the selected concept and work through the steps shown in figure 2, producing a preliminary layout and determining the definitive layout in form of a design structure (overall layout) of a technical system in accordance with technical and economic requirements. The last phase is the detail design phase, where the arrangement, forms, dimensions, surface properties, etc. of all the individual parts are finally laid down. The documents concerning specified materials, assessed production possibilities, estimated cost, and all the drawings as well as the other production documents have to be produced in this phase. All documents needed for the specification of the production are expected to be ready after this phase.

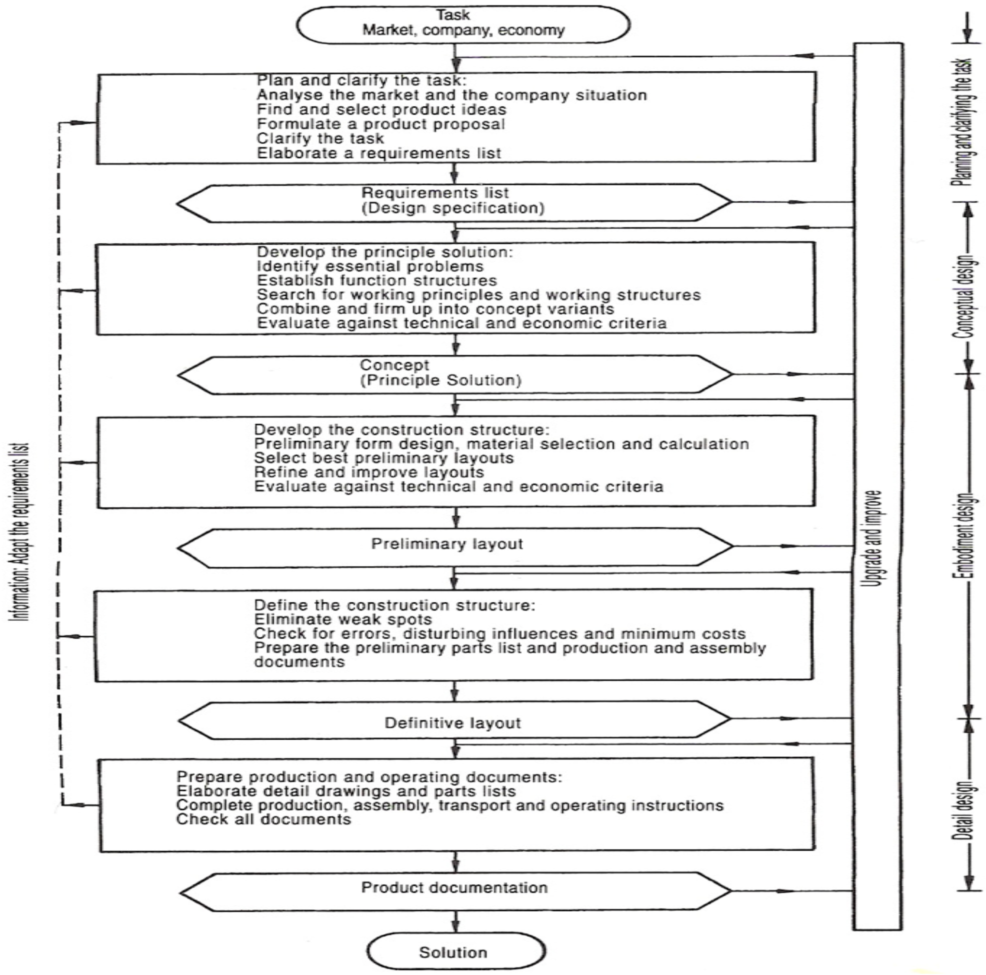

Figure 2: Pahl & Beitz Design Methodology [10]

3 INDIVIDUAL DESIGN PROCESS: DEVELOPMENT OF A PIEZO-ELECTRIC BRAKE

3.1 Piezo-electric Materials

Piezo-electric materials are considered as one of the existing smart materials due to their special characteristic of producing voltage upon being subjected to stress. In addition, this effect also works in reverse direction, in which applying voltage across the material will produce stress within the material. This phenomenon is known as the piezo-electric effect. Many applications and devices have been invented using the principle of the piezo-electric effect. For instance, anti-shake mechanism for cameras, electric cigarette lighters and gas-grill lighters are among the applications of the principle of the piezo-electric effect, which have given a great impact to our daily lives. The significant innovation found in these devices is the fact that they come in much smaller sizes. Moreover, piezo-electric materials have a various and wider range of applications because of their ability and durability in producing high force due to the generated stress when voltage is applied. In mobile robot applications, where space is very limited and the increment of sizes is almost proportional to the cost, every device used has to be as small and compact as possible. Size is one of the main critical criteria that have to be considered when designing any devices for mobile robot applications. Thus, with the aim of building a small device that would be able to generate high force for braking purposes, a piezo-electric material had been selected for this project. The piezo-electric brake in this project is designed to consume the least space as possible and hopefully will initiate its application in mobile robot applications.

3.2 Design Process

In the development of the piezo-electric brake, the design methodology suggested by Pahl & Beitz [10] has been used along with the V-model suggested by the VDI guideline 2206 [8], which acted as the process model. The selection has been made due to the fact that this project involved the development of a mechatronic product which demanded a participant or knowledge from three major engineering disciplines, which are mechanical engineering, electrical engineering, and computer science. Since V-model is very useful in dividing a development work into the respective engineering domains, it makes the development process much more organised and transparent. Besides, the V-model also provides a clear structure of the development process from one level into another. Therefore the combination of both the V-model and the Pahl & Beitz design methodology was to ensure a systematic and organised procedure or development process for the piezo-electric brake [11]. Figure 3 shows the process model used in this project to develop the piezo-electric brake system.

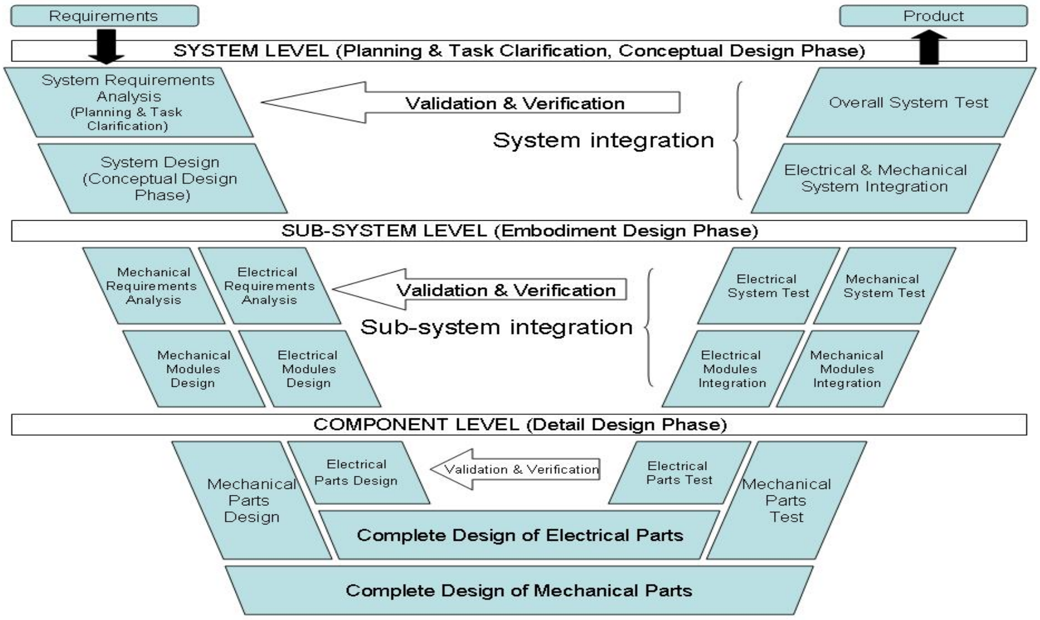

Figure 3: Process Model for the Development of the Piezo-electric Brake

This process model is a result from the modification and combination of the V-model of the VDI 2206 and the Pahl & Beitz design methodology. Generally this process model and the system itself can be divided into three main levels: system level, sub-system level and component level.

As in the V-model from the VDI 2206, the main goal on the **system level** is to produce a cross-domain solution principle, which thoroughly describes the main physical and logical operating characteristic of the system or product, which is going to be developed. Therefore, the planning & task clarification phase and the conceptual design phase of the design process is carried out on the system level.

On the **sub-system level** the solution principle is divided into the respective domains involved. As for the solution principle of the piezo-electric brake, since it consists of the mechanical and electrical operating principles only, the design process of the piezo-electric brake is divided into two main engineering domains, which are the mechanical engineering and electrical engineering domain. After the division, the embodiment design phase proceeds separately in the respective domains (compare [12]). The milestones of the sub-system level after completing the embodiment design phase are a rough layout design, which consisted of a general arrangement and spatial compatibility of the respective mechanical and electrical systems as well as the preliminary parts list for reference purposes when doing the detail design phase in the component level.

On the **component level**, a further concretisation of the parts in each system is carried out. In terms of Pahl & Beitz, this constitutes the detail design phase which involves activities like detail design of the parts, detailed calculation, parts analysis, etc. At the end of the detail design phase, the complete design of the mechanical parts as well as the electric parts has been produced. Next, all of these parts are documented. Testing is conducted later on to validate and verify all these parts to ensure that they have been designed according to the specification prescribed in the requirements list. The next task is the first integration process of the parts. This first integration process is known as the sub-system integration, which is done in the respective domains.

In the **sub-system integration**, all the mechanical or electrical parts are integrated to form a complete mechanical or electric system within the respective domain. System testing is conducted to ensure that

each part in the systems is compatible to all the other parts as well as to check whether the systems perform with all the required functions as stated in the embodiment design phase previously. After the systems pass the system testing, a complete production document of each domain, which covers the method of manufacturing, assembly, transport and operating instructions, is generated.
This is followed by the integration between the electric and the mechanical system. This integration process is commonly known as **system integration** since it takes place on the system level. As in the sub-system integration, an overall system check is conducted to test the compatibility between the mechanical and the electrical system before the decision is made whether or not the overall system has fulfilled all the specification as requested in the requirements list. Lastly, a complete product documentation of the developed product is finalised.

3.3 Product Development of the Piezo-electric Brake

3.3.1 Planning and Task Clarification Phase

From the planning and task clarification phase, a requirements list to accumulate the required specification for the piezo-electric brake was formulated. This document forms a measure against which the developed piezo-electric brake was to be assessed.

3.3.2 Conceptual Design Phase

A function structure had been established from the overall function for the purpose of problem abstraction. Figure 4 shows the overall function and function structure for the piezo-electric brake.

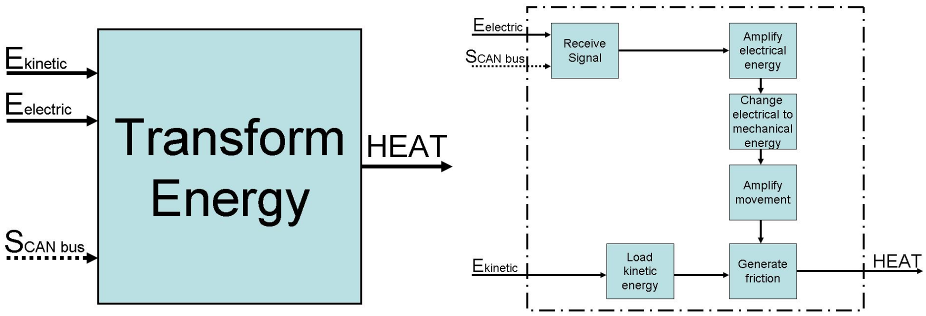

Figure 4: Overall Function and Function Structure of the Piezo-electric Brake

Based on this function structure, suitable working principles have been searched for each sub-function. Figure 5 shows an example of working principles that have been derived from the physical effect of one sub-function.

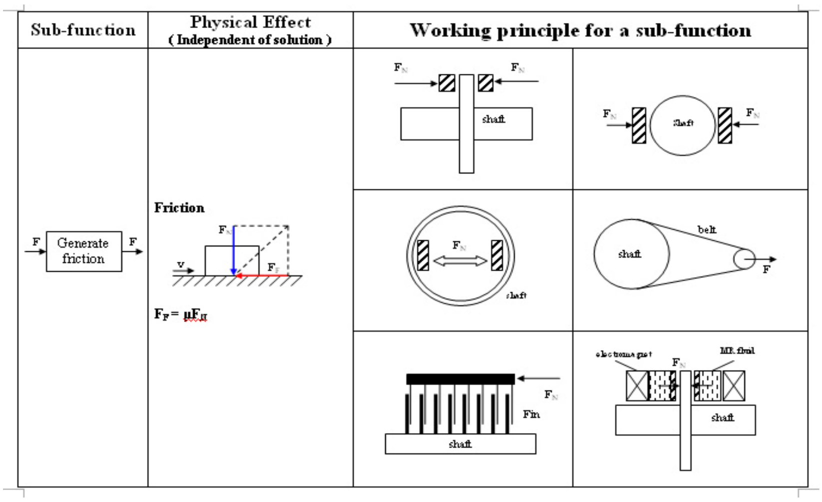

Figure 5: Working Principles of a Sub-Function

All the working principles that fulfilled the demands of the requirements list were selected and combined to form a working structure. The working structure was then firmed up and this activity led to the forming of principle solution variants. Figure 6 shows principle solution variants for the piezo-electric brake.

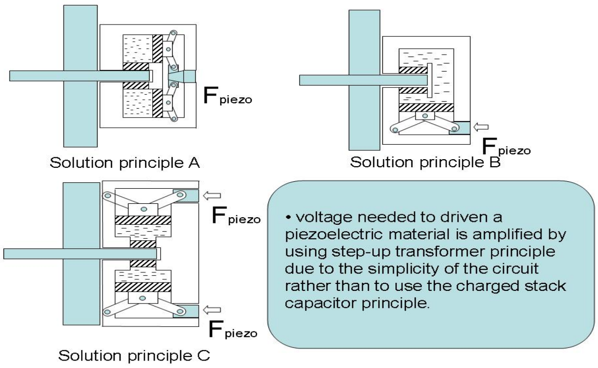

Figure 6: Principle Solution Variants for the Piezo-electric Brake

In order to select one principle solution variant, an evaluation process was initiated. The evaluation criteria were functionality, working principle, embodiment and safety (Table 1)

Table 1: Principle Solution Variants Evaluation Criteria

No.	Main heading	Evaluation criteria
1	Function	Fulfil all the required functionalities in the requirement list
2	Working principle	Simple and clear-cut functioning, adequate effect, few disturbing factors
3	Embodiment	Small number of components, low complexity, low space requirement, no special problems with layout or form design
4	Safety	No additional safety measures needed, industrial and environmental safety guaranteed

As the result of the evaluation process, solution principle C was selected. Some modifications were also suggested to the solution principle C, which then resulted in the final solution principle as shown in Figure 7.

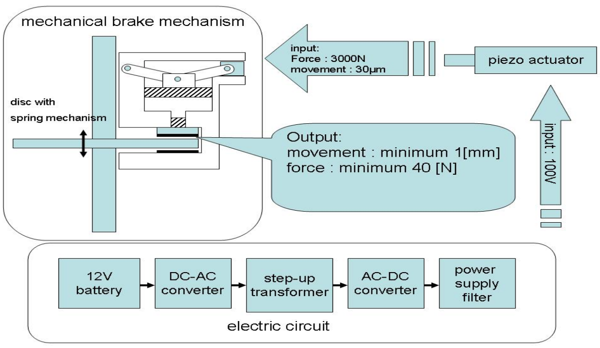

Figure 7: Final Solution Principle

3.3.3 Embodiment Design Phase

The embodiment design phase was started by dividing the solution principle into the respective engineering domains. The sub-system of each domain was further divided into several modules to ease the painstaking design work. Figure 8 shows the modules contained in the mechanical and electrical engineering domain.

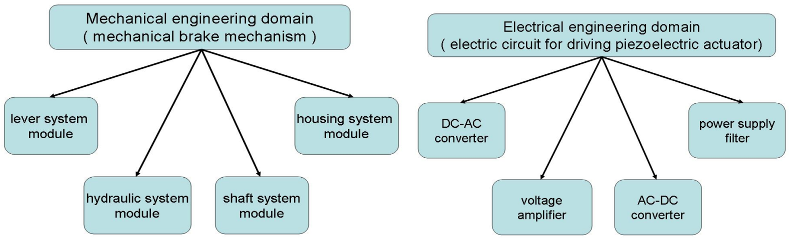

Figure 8: Mechanical and Electrical Engineering Domains' Modules

Next, the conceptual design task for each module was carried out. The aim of this conceptual design process was to produce a rough layout for each module. Upon completing the design of each module, an evaluation against technical and economic criteria was carried out for each module. Based on this evaluation, optimisation measures of the designs were specified. This optimised design was called definitive layout and consisted of a rough layout including the functionality of each module. Finally the preliminary list of each part was produced for reference purpose in the detail design phase.

3.3.4 Detail Design Phase

All the detailed drawings for the mechanical parts and electrical parts as listed in the preliminary parts list were done in this detail design phase. The related calculation of each part such as pin calculation, hydraulic cylinder thickness, and calculation for Belleville spring were done here, too [13]. At the end of the detail design phase, all the information regarding the mechanical parts and electrical parts were documented. These documents are important for production purposes.

3.3.5 Sub-System Integration Design Phase

In the sub-system integration design phase, all the mechanical parts and electrical part were integrated within their domain to form a complete mechanical and electrical system. Figure 9 and 10 show the results after the integration processes of mechanical parts and electrical parts have been completed.

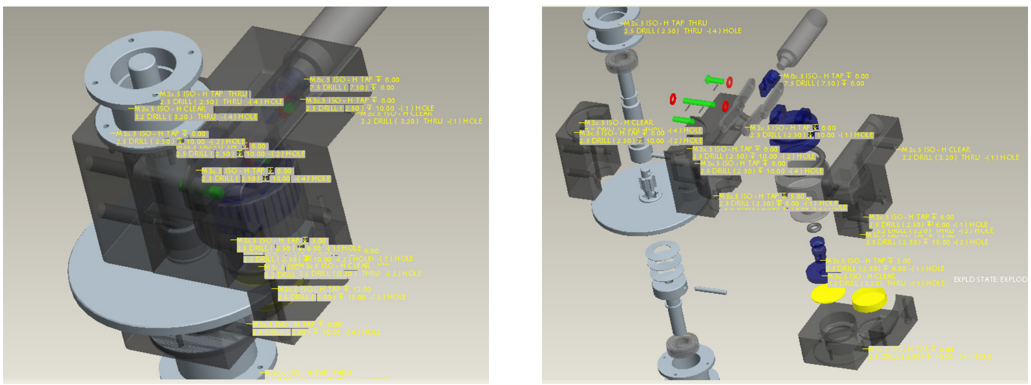

Figure 9: Piezo-electric Brake (Mechanical Integration)

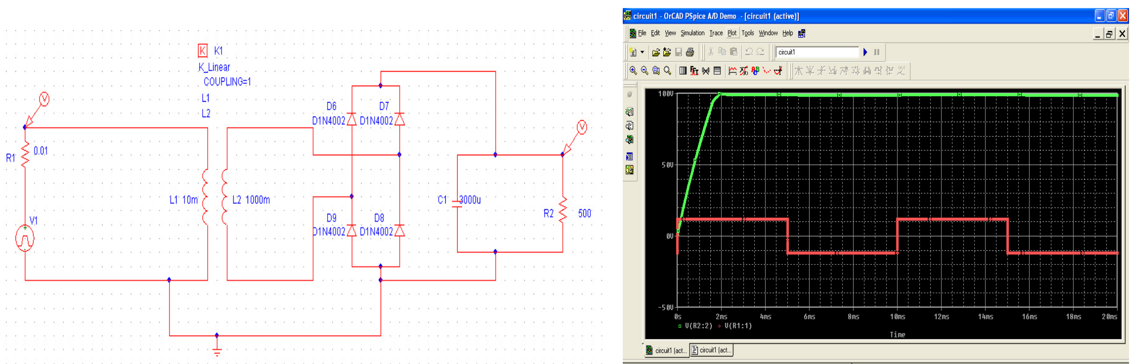

Figure 10: Electric Circuit for Driving the Piezo Actuator (Electrical Integration)

As for the electrical system, simulation was conducted to ensure that the electric circuit can achieve the result as required. The simulation results verified that the electric system fulfilled the requirements to drive the piezo actuator. The system integration design phase was not done in this project due to the development time constraint as well as the lacking of man power. Thus, it hopefully will gain an interest from the next developer for improvisation in this area in future.

3.4 Conclusions concerning the application of the V-Model

In general, the experience in the development of the piezo-electric brake makes clear that the V-Model presents a suitable structure for the development of mechatronic products. The application resulted in a functionally novel design. The decomposition into system level, sub-system level and component level structured the design process and helped the individual designer to keep an overview of his design process. However, considerable problems were identified during the application of the V-Model in the small design process. The main focuses of the V-Model are the electric and electronic systems and the software. The specific challenges of developing mechanical hardware are not sufficiently addressed. Furthermore the V-Model as well as many other methods and tools for the development of mechatronic systems (compare [14], [15], [16]) is focused on analysis. Specific support for the synthesis of systems and components is nearly completely missing. Therefore the combination of the V-Model and the VDI 2206 with a "classical" design methodology such as Pahl & Beitz seems to be a promising approach. Additionally, in accordance with other research results (e.g. Stetter & Lindemann [17], Lindemann [18]), it became clear that only a conscious, flexible, and situation oriented application of the methodology and the processes is sensible.

4 LARGE SCALE DESIGN PROCESS: V-MODEL AND MECHATRONIC DESIGN IN INDUSTRY

4.1 Current situation

Mechatronic design has long become the major part of industry, hardly any product can live without electronic or mechatronic elements. Electrics and electronics (E/E) are due to their complexity the major source of failures in products; but understanding complexity [19], it is not the sheer amount of circuits and program codes allowing many mistakes, but the interaction of hundreds and thousands of separately working functions and variables.

As an example of highly complex mechatronic products, we would like to look at the engine of a modern automobile. Many new technologies such as direct injection can only be handled by intelligent steering algorithms; many innovations can only be implemented by software and electronics. Actually, the whole control of the engine has become—from a mere opening of the throttle—a complex interpretation of the driver's demand for torque, combined with the current driving situation, demands for energy, interferences of electronic "leprechauns" such as automatic stability control, etc.

Yet, it is important to consider the situation in which such complex products are being developed. Though there are many innovations and new technologies, new products are largely based on and match existing products. This is necessary in order to understand the functioning of the product, its behaviour, its requirements, its problems, etc.; but it sometimes lets people and organisations stick to existing solutions. It is a tightrope walk between the cultural, evolutionary, and technological use of existing solutions and the progression to new solutions.

As in many other industries, the development has to react to late changes of the requirements, which again can only be derived after a first concept exists. Iterations and buffers, if additional development efforts are needed after elaborating and evaluating product properties have to be provided for. While as always iterations due to new requirements are hardly considered, iterations due to the integration of different modules and the only then possible evaluation of product properties form a major part of the design process. Still it is a question how many iterations are ideal: should there be a fixed amount of iterations, should there be as many iterations as possible in a certain time frame, or should the amount of iterations be reduced in order to have more time for each iteration?

And even the iterations are only part of the complex design process and not clearly identifiable. The iterations of decomposition and integration are overlapped by continuous and concurrent development activities on each and all system levels and embedded into a complex process landscape covering e.g. requirements management, synchronisation plans, configuration management, testing, risk management, modularisation strategies, etc. Such a process landscape is the only way to organise, structure, or control a complex organisation, i.e. to handle the complexity of a big company. It is illusionary to map *one* sophisticated process onto a big social system with many individuals; by the way, this would also contradict the emergent functioning of interacting people on a new level of complexity. In the same way, a relatively simple model such as the V-Model cannot cover the whole design process nor be easily transferred to the design process without comprehensive adaptations.

4.2 Implementation of the V-Model

The use of the V-Model in a complex organisation thus needs the transformation and adaptation of the model into industrial processes (Figure 11). While some processes and approaches are well established and rather run in parallel to the V-Model, such as project management, quality management, or configuration management, other processes fit more clearly into the V-Model, especially requirements management and verification & validation. Even if the V-Model is not the initiation of these measures, the need and start-up of them shows that the V-Model is also appropriate on a company level; it also helps combining these processes, i.e. clearly showing their interactions.

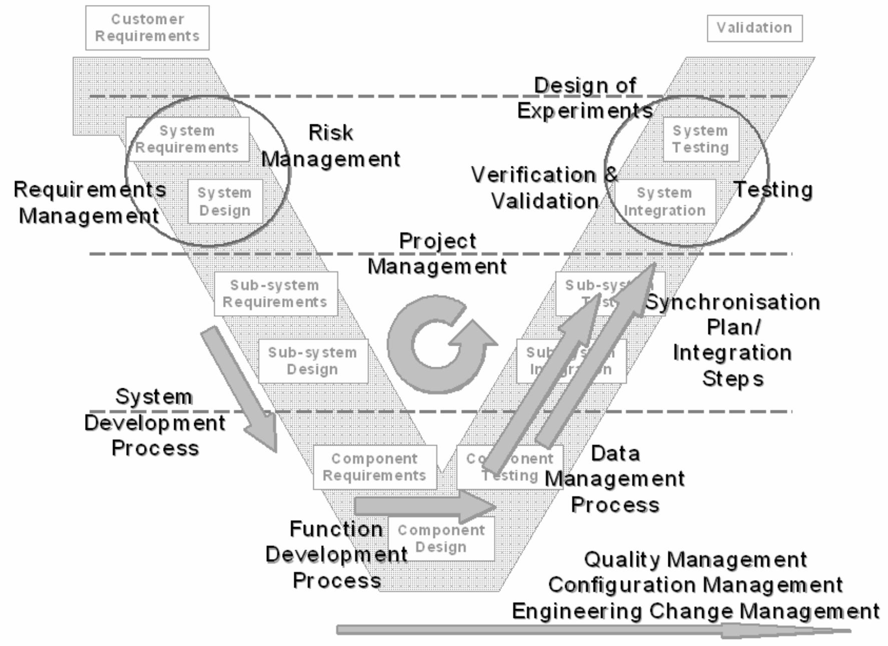

Figure 11: V-Model and related processes

Requirements management covers the requirements development, the tracing of requirements to technical solutions and vice versa, and the decomposition of requirements or higher level solutions to requirements on subsystems. By applying requirements management simultaneously to the design process and using respective computer support, the design logic will be comprehensively stored, helping future projects in their development. Requirements management is also necessary and the basis for the evaluation of the concept and the testing and safeguarding of product properties.

Testing, i.e. verification & validation and especially the search for failures, represents the right side of the "V". Testing again demands for a comprehensive requirements management, i.e. a collection of test cases, as well as a statistical planning of relevant tests and relevant variants, and the appropriate sourcing of respective experimental vehicles, all of which are constraint due to the large amount of variants and theoretical test cases on one hand, the costs of prototypes and the limited resources on time and test equipment on the other hand. Only the application of a statistical design of experiments combined with a sensitive risk management ensures the demanded quality of the product.

Furthermore, testing has to be distinguished to different occurrences: the final testing of the whole system from a customer's point of view—which might also be the legislation or workshops—, the testing of the interaction of different subsystems from the engineers' technical view, as well as the testing of subsystem properties, i.e. experiments to find out the behaviour of a subsystem, which is interlinked with the design process. All of these kinds of testing can happen on all levels of the V-Model, actually the tests might be the same or quite similar, but their intention is different and it is

necessary to distinguish them in the process, otherwise there would be too many or continuous changes and adaptations in the late testing phase.
A way to distinguish these levels is the amount of application data that is changed. The software of an engine or of a mechatronic system in general can be divided into two parts: the functions, i.e. the program code, which by different methods hardly contains any failures; and the data or labels, with which the software is adjusted to the hardware or the whole system is tuned, which due to their amount and interactions is the source of unexpected behaviour and failures.
The testing together with the development aims to set those labels or define the data for each subsystem, the integration tests should help adjusting labels to the interaction of different functions, while the final safeguarding should not be interlinked with changes of labels, but identify failures from a customers' point of view.
While the V-Model just proposes the integration on different levels of the system, the actual design process is strongly driven by so-called integration stages, which happen regularly and integrate the design status of different departments in order to test the whole system behaviour and properties. These stages somehow form iterations of the V-Model, though they are mainly restricted to the integration phase, i.e. the adjusting of the subsystems and not the requirements development. By that, the data of the software can be seen as part of the detailed design of the V-Model (bottom) or as part of the integration of the V-Model (right top), depending on whether you see the V-Model as a model for the levels of the mechatronic product or as a time-oriented process model.
In order to regard and use the V-Model as a process model, a detailing of the model with more prescriptive steps and respective methods is necessary. This can be accomplished by combining the V-Model with the process model of Pahl & Beitz and/or similar and respective models. This quite easily realisable combination shows that both models are not far from each other and definitely do not contradict each other, but just emphasise different aspects. The approach proposed in this paper is thus also feasible for industrial development processes in big companies. Since the model is generic and represents a logical proceeding, the problem is not the feasibility of the model itself, but how to apply it to everyday development activities.
Finally, the implementation of the V-Model and the described processes conform with the CMMI (Capability Maturity Model Integration) approach [20], which looks at the development of the organisation similar to quality management and process orientation. It is also supported by a function orientation, i.e. a focus on functions and systems rather than on parts and components.
The V-Model can also be applied to more mechanical problems, e.g. in the aerospace industry, where the design process is a back and forth of detailing of the whole system into subsystems and an integration of the—eventually pre-developed—subsystems into a complete system.
The V-Model thus is appropriate for mechatronic and mechanical design, yet there are some difficulties especially when looking at predominantly mechanical products, which can be overcome by combining it with approaches from the design methodology.

4.3 Difficulties with the V-Model

Some of the difficulties of the V-Model have already been indicated in the previous chapter, they shall be addressed explicitly below. For some of these we can hint at solutions, some still need further consideration by the design methodology.
The V-Model is focused on E/E and software, not on mechanical hardware. Guidelines and tools for the decomposition and integration of hardware are missing or have to be added from the classical design methodology, especially since the regarded products are predominantly mechanical. It should not be a problem to extend the V-Model to mechanical aspects, but nevertheless, guidelines for the technical design of mechatronic components are not apparent yet, the proceeding of a strongly integrated mechatronic development is still unclear, i.e. how does—or can—a mechatronic system look like. Understanding is missing and, though the domain-specific design is right at the moment as a first step, a new way of thinking and education seems to be necessary. System thinking or system orientation might be the right approach, together with a mechatronic systems architect, who is still missing.
A more serious problem might be that different integration directions have to be considered. While the integration of mechanical, E/E, and software components happens on a subsystem level, on the complete system level both different mechatronic subsystems and the mechanical parts geometrically, the E/E components electrically, and the software components functionally have to be integrated

separately. The same holds for the decomposition of the system and its requirements. The V-Model doesn't address these multiple integrations and this difficulty is practically approached by respective organisation measures with different stakeholders. The integration is aggravated by functional overlapping of subsystems, the collaboration with suppliers, etc. The integration is also aggravated by the amount of variants and different development stages. The continuous "seesaw" between decomposition and integration or iterations are not clearly addressed in the V-Model as well as the concurrent development on all levels of detail of the system at the same time is not considered practically; a clear distinguishing between these levels might not be possible and the V-Model has to be understood as a way of reflecting these levels rather than a temporal proceeding.

The multiple and complex integration also demands for development activities during this integration, i.e. application or the setting and adjusting of labels and data. This might lead to the fact that development and testing as well as sometimes even requirements development cannot be practically distinguished, as it is found in industry, too. This again might lead to a 'never ending' development process. The V-Model can help overcome this if understood appropriately; but it should emphasise this aspect even more and respond to this practical problem explicitly.

For practical purposes, the V-Model should also propose methods for concept design, concept validation and testing, as well as system analysis, such as UML elements, phase diagrams, functional analysis, system structuring, value analysis, design of experiments, etc. Especially for the concept design, parts of complexity management and design for variation as well as variations as a design principle have to be integrated. The implementation of the design methodology and the "thinking in alternatives/variants" is both important and difficult since the practical proceeding in development of new products in general are based on existing solutions and "thus" a methodology or a systematic proceeding does not seem to be needed by some people.

There might be some more problems occurring while implementing the V-Model that are not directly related to it. These are e.g. politics within the company, a locally distributed work environment, the general contradiction of methods either being too general or too specific, the discussion on methods being prescriptive or descriptive, or the often found "babel", the confusion of words used differently in different contexts (such as system, function, etc.). These difficulties are important to consider simultaneously to implementing the V-Model, but cannot be addressed in detail here.

4.4 Approaches

Mechatronic design is not a one-way communication, where mechanical design gives requirements do E/E and software components; this might have been appropriate as a first step towards mechatronic products or predominantly mechanical products, but it doesn't realises the full potential of mechatronic design and does not correspond to the complexity of current products.

A first model for mechatronic design is the V-Model, but it originates from software design and thus has to be transferred to mechatronic design and extended by respective methods and processes for the actual design of the product or industrial contexts respectively. It seems to be appropriate to combine the V-Model with a traditional model from mechanical product development such as the Pahl & Beitz approach and respective methods, as proposed in this paper. This exercise also shows that these models or proceedings are not too far from each other. Some of this has already been presented in the VDI 2206, but it is necessary to emphasise and detail this approach as well as to show its practical applicability and its relevance for industrial environments by extending or leveraging it with respective processes such as requirements management, test planning, systematic development, system orientation, CMMI, reorganisation measures, process management, function orientation, etc.

This contribution can only hint at the direction where to go with mechatronic design and the V-Model, more details will have to follow. The industrial need for a methodical support of mechatronic design exists and grows steadily.

5 CONCLUSION

From the results obtained during the analysis of two diametrically different design processes—the individual design process of a piezo-electric brake and the product development process for engine controls in automotive industry—it can be concluded that the combination of the V-Model and a classical design methodology (in the presented case the Pahl & Beitz design methodology) has the potential to successfully organise design processes of mechatronic in a systematic manner. In contrast to other approaches this combination provides support for the synthesis of mechanical sub-systems and components. This difficult and challenging endeavour has frequently been neglected in mechatronic literature. Therefore the presented addition to the VDI guideline 2006 can be one component of a future detailed systematic mechatronic design methodology. It is important to note that the results presented in this paper are only based on the analysis of two product development processes. Future research is necessary to accomplish validity and general applicability.

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