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A PROPOSAL FOR THE USE OF DIAGRAMS OF UML FOR MECHATRONICS ENGINEERING

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1. Introduction

This paper intends to explore the use of the diagrams of UML (unified modeling language) in the product development of mechatronical products. The analyzed product development process concerns the development of a brake for a mobile robot. The patented steering principle of this robot is based on torque and speed differences [described in Zajac et al. 2007]. This kind of steering system can be enhanced by the equipping the steering axles with brakes. The developed brake uses a smart material – a ferromagnetic shape memory alloy (FSMA) – and has the unique characteristic to compensate wear and tear. The embodiment of the brake has already been registered as a patent. The experience during this development was used to reflect on an appropriate methodology for mechatronical design. Earlier efforts to improve the methodology for mechatronical product development [Rahman et al. 2007] focused on a combination of the V-model with conventional design methods. The background of the methodology is explained in section 2. A combination of the well-known V-model as suggested by VDI 2206 [Gausemeier&Möhringer 2003, VDI 2004] and the systematic design methodology described e.g. by Pahl and Beitz [Pahl&Beitz 2004] was applied in the example development process. As an improvement of the combined methodologies, UML diagrams have been used as a design tool at the various stages of a design process. In section 3 the product development process is described. The reflection of the application of UML diagrams for modeling this mechatronical product is given in section 4.

2. Background

Mechatronics design has been in the focus of research for some years [Buur&Andreasen 1989, Buur 1990]. Several current publications aim at supporting the development of mechatronical products [e.g. Alciatore&Histand 2003, Czichos 2006, Roddeck 2003]. However, most publications focus on analysis and on the electronic and software components. Recent scientific publications also cover the modeling and simulation of mechatronical systems [e.g. Stechert et al. 2007]. In this section the most considerable methodology for mechatronical design which also covers the synthetical aspects of design – the application of the V-model as suggested by VDI 2206 [VDI 2004] - is briefly presented as a main basis for this research. In the second part of this section a combination with the systematic design methodology described by Pahl&Beitz [2004] is presented.

2.1 V-model

The V-model is an industrial standard introduced by the German Federation which represents a model of system development cycle. The VDI 2206 [Gausemeier&Möhringer 2003, VDI 2004] is a specific standard for the design and development of mechatronical products. The V-model process starts with a requirement list. In the "system design" phase the designers will work based on the requirement list. In this phase, the system design is divided into domain specific designs according to their respective engineering field. In its respective field each domain will solve its engineering problems. The outcome of this phase is integrated in the "system integration" phase. Testing and validating effort will be done from the beginning stages continuously to reduce problems in the later stages. The final mechatronical product is expected to be flawless, assuming that enough tests, integration and validation efforts have been done.

2.2 Combination of the V-Model and the Systematic Design Methodology by Pahl&Beitz

One of the most significant design methodologies is described by Pahl&Beitz [2004]. This methodology is well accepted in Mechanical Engineering field. An effort has been done by Rahman et al. [2007] to combine the above methodologies. It was concluded that these two methodologies are complementing each other and thus provide an improved methodology for the development of mechatronical products The V-model is useful in dividing the system into the engineering domains while the systematic design methodology by Pahl&Beitz is especially useful for dividing the design process into several design phases and providing precise methods for the distinct product development steps. **Figure 1** shows a combined structure of these methodologies.

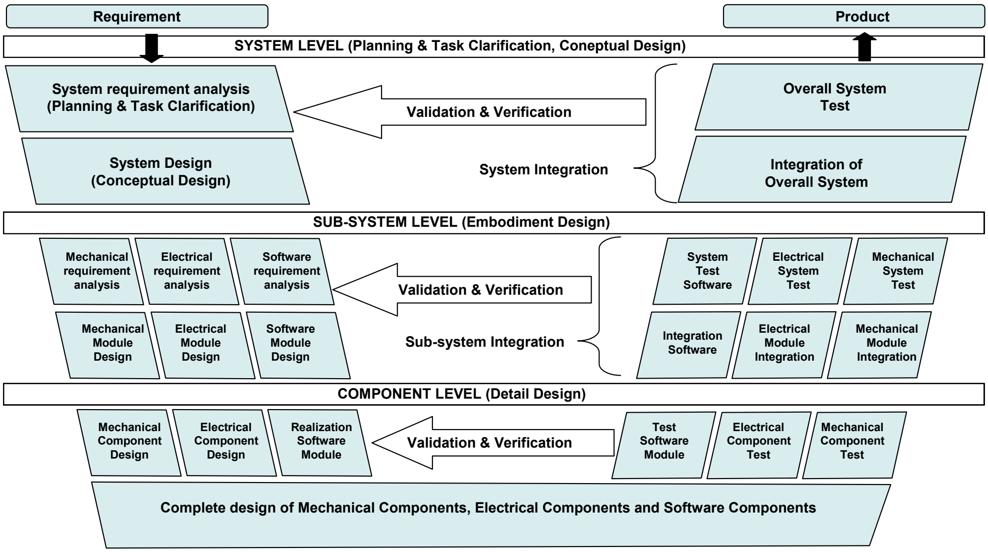

Figure 1. Combined structure of a design process for mechatronical products

It is important to note that the combined structure is not intended to be used as a project plan but rather as a process map. These structures help engineers to understand the logical structure of their procedure and to determine the next sensible steps. The planning of time spans, milestones, etc. has to be carried out simultaneously. This process map therefore does not show iterations. However they inevitably exist in any development process. The integration of all iterations in a process map is not advisable for the sake of simplicity and clearness. Furthermore it is important to note that this structure is only a macro structure of the development. It has to be accompanied by a micro-structure, usually a problem solving cycle which is repeated again and again through the development process. For this purpose for instance the problem solving cycle of systems engineering [Daenzer&Huber 1997] can be adopted. Finally it is important to note that it can be necessary to run several cycles through the V-Model on different levels of abstraction to obtain a market-ready product.

2.3 UML 2.0

The UML 2.0 is a modeling technique that has been introduced for software engineering [Ambler 2004]. This modeling technique is used in the early stages of a system software development. UML diagrams are divided into two major groups which are structure diagrams and behavior diagrams. Designers can choose from these two types of diagrams depending on their specific modeling demands. More than one type of diagram can be used to model a system as this might help the designers to get a better insight of the system. The “class diagram” is the most important diagram of the structure diagrams. This diagram shows a collection of static models of subsystems and the relationship between them. Each class is represented together with the attributes of the class and an operations list. The attributes of the class provides information on the parameters involved and their initial value. The operation list provides an overview of the arguments of the class. The interaction between the classes allows an overview of how the system works. Another important diagram in the UML modeling technique is the “use case diagram”. This diagram falls into the category of behavior diagrams. This diagram shows the actions and the reactions within the system. The diagram is built by a group of actors which represent every element in the system. The use cases are used to show the activity in the system. The use case connects with actors that are involved in the actions. In this research, these two diagrams were used to model the product. These diagrams will be integrated together along the design process as a part of a process model of mechatronical products.

3. DESIGN AND DEVELOPMENT OF A BRAKE SYSTEM USING FSMA

3.1 Ferromagnetic Shape Memory Alloy (FSMA)

The ferromagnetic shape memory alloy or also known as the FSMA is a material that possesses the ability to produce stress and strain under certain conditions [O’Handley et al. 1999, Ullakko 2000]. When the material is exposed to a magnetic field it will produce strain and will return to the original condition when there is no magnetic field present. The linear function between the magnetic field and the produced strain makes this material easy to control for any application. The fact that the magnetic field has a high frequency response makes this material suitable for high frequency applications. This material has the potential to replace conventional actuators such as pneumatically, hydraulically and electromagnetically driven actuators. In this research a brake system which applies the FSMA as a brake actuator was developed for robotic application. The robotic application [compare Stetter et al. 2006] has a strict requirement in terms of weight, size and simplicity of its design. By applying the FSMA all these strict requirements can be realized.

3.2 Design Process

In this research a methodology was chosen which is a combination of the V-model and the systematic design methodology described by Pahl&Beitz [2004]. The UML diagrams were used as system modelling tools. This project involved three major engineering domains which were Mechanical Engineering, Electrical Engineering and Computer Science. By applying the combined methodology a systematic and efficient work flow towards the development of the mechatronical product was achieved.

The UML has a major influence on the early stage of product development. In this research the “use case diagram” was used to model the overall system concerning the robot and the brake system. Based on this model a requirement list was created. The “system level” of the brake system is then entered by the design processes. At this stage the activities concern planning and task clarification. Based on the requirement list a further refined UML model was developed. In this research another “use case diagram” was created to give more details about the brake system. This diagram is more concentrated to the brake system itself. Based on this, a system requirement analysis was carried out to help the designer to make several important decisions about the product design such as the type of smart material to be used.

The next stage is the conceptual design phase. At this point the concept design was supported by a “class diagram” of the brake system. In this “class diagram” a clear picture of the system layout with

every involved engineering domain was shown. By the application of the “Class diagram” several possible solutions could be developed.
The design processes then enters the sub-system level where the embodiment design is generated. In this level the V-model structure helps to divide the system into three engineering domains. The UML diagrams again can play a pivotal role to guide each engineering domain. A “class diagram” was created for each engineering domain as a reference for the creation of the respective requirement analysis. At the end of the embodiment design phase several module designs were created that provided the designer with a diversity to choose an optimal solution. After considering all technical and economical factors, a final layout of the system could be decided on at this phase. The process model is now at the component level where the detail design phase is performed. For mechanical engineering domains, each component was designed and drawn using CAD software programs. The simulation of the final assembly of the brake system was performed to ensure the absence of problems during the integration process in the later stages. For the electrical engineering domain and the software engineering domain similar activities were carried out and the electrical circuitry in the brake system was simulated.

3.3 Product Development of the FSMA Brake applying UML

Prior to the system level, a model of the overall system has been created using the “use case diagram”. **Figure 2** shows the “use case diagram” of the overall system. From this use case diagram a general requirement list has been created.

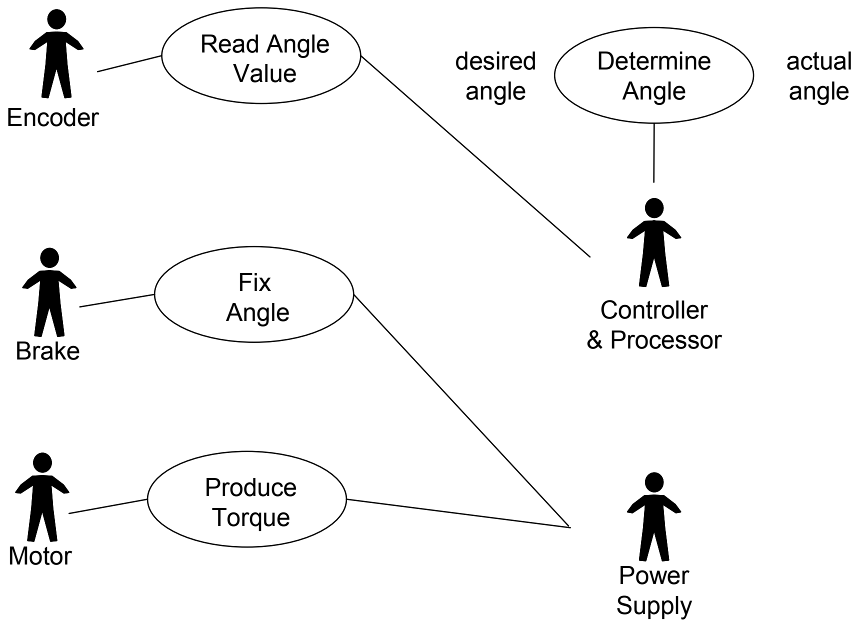

Figure 2. “Use case diagram” of the complete system

At the conceptual design stage, a model can be used to assign subsystems and components to the respective engineering domains. A “class diagram” was used to model the brake system at this stage. The diagram clarifies the engineering domains and their interaction. **Figure 3** shows the “class diagram” of the brake system. Based on this model several suitable working principles were searched for each class. These working principles which fulfill the requirement list could then be selected and combined to become a concept design. In this development process five concept designs were created with a total of seven design variations.

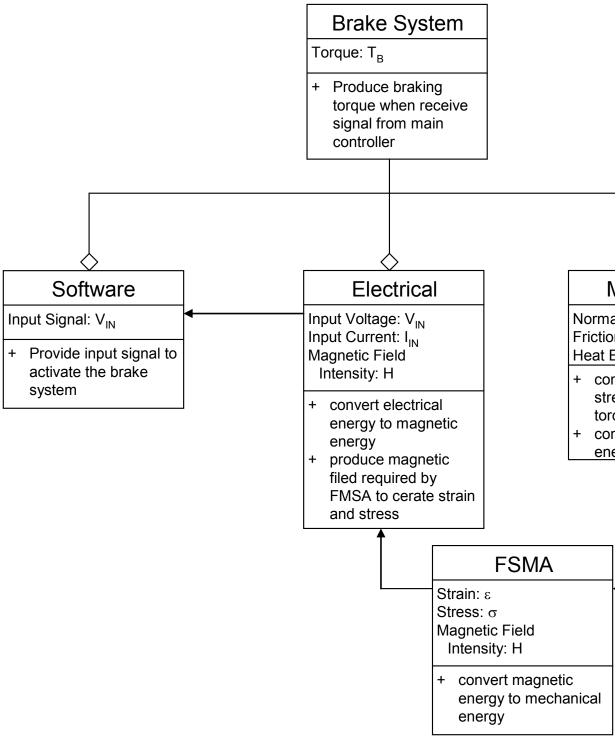

Figure 3. "Class diagram" of the brake system

All these designs fulfill the requirements and have their own advantages and disadvantages. After a careful consideration the two best designs were selected to be further detailed in the embodiment design phase. **Figure 4** shows the embodiment of one of the solutions.

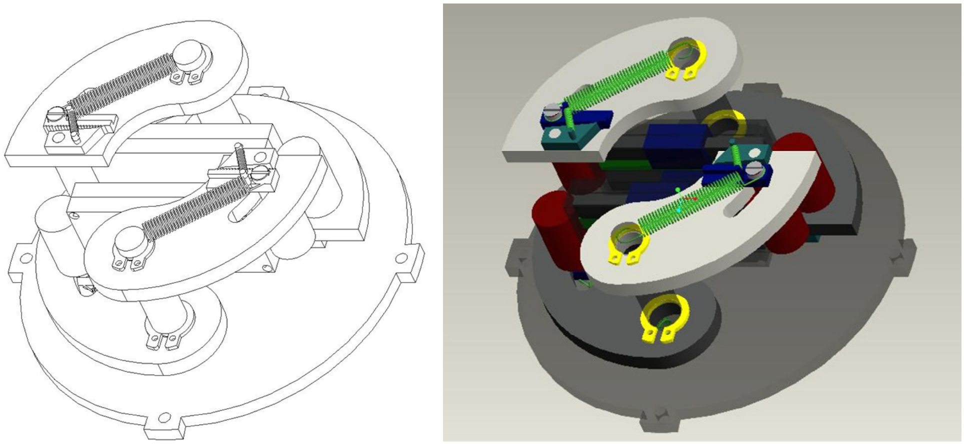

Figure 4. The final assembly of design one (mechanical domain integration)

4. Reflection of the application of UML

In this research an approach was made to apply UML diagrams to model a mechatronical system including mechanical subsystems. It was observed that applying these diagrams during the design process really helped the designers to understand the system and their contribution to it. It can be hypothesized that a better end result was achieved because more potential concept designs have been produced than in comparable developments in the same department.
However using the UML diagrams the authors faced problems. The fact that these diagrams have been created for the application of software engineering results in the circumstance that some of the terms and the definition of the diagrams are not suitable for a physical system like a mechanical system. An adaptation effort needs to be done in order to make it applicable for modeling a physical system. A set of alteration of definitions was developed so that designers from other engineering domains can utilize these modeling methods. **Figure 5** shows an example of the alterations of the "class diagram" that have been done in this research.

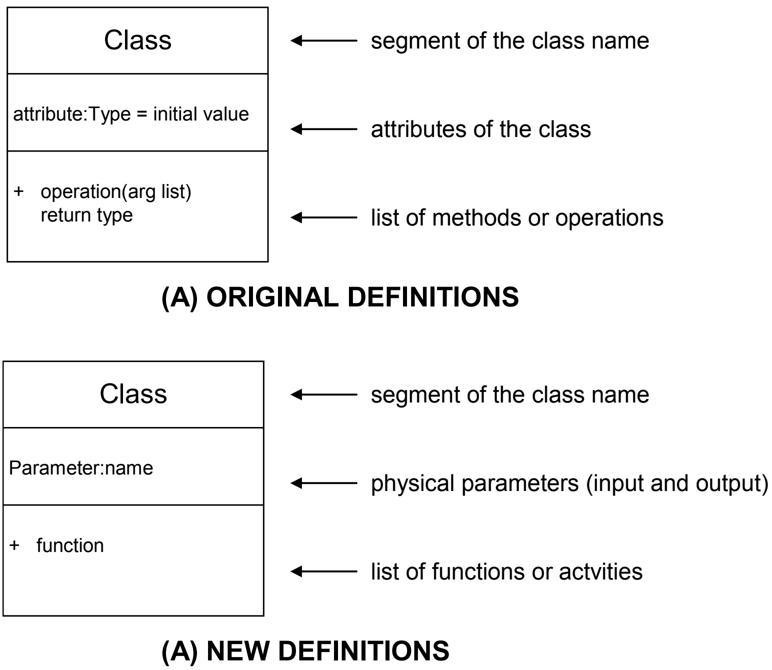

Figure 5. The alterations of definition of UML diagrams

In order to utilize the UML diagrams in the optimum way, it is recommended that designers use both types of UML diagrams. This is important as behavior diagrams and structure diagrams will give a different view about the system. By having both sets of diagrams more information and ideas can be generated. The designers have the freedom to choose which diagram they want to use.
The outcomes of the UML modeling techniques provide a perfect platform for the next step of the modeling process. The UML diagrams have successfully modeled the system and divided it into their specific classes. These classes can then be used as inputs for the domain-specific modeling language. One of the most significant domain-specific modeling languages is Modelica. Modelica is an object-oriented programming that is capable to do modeling and simulating a complex system. Modelica provides a wide range of libraries that includes many engineering domains such as Mechanical, Electrical, Electronics, Pneumatic, Hydraulic and Control. The libraries list continues to grow as more researchers from many engineering disciplines are developing their engineering model libraries.

Modelica libraries are built by the mathematical models of the system. A complex physical system is build by several sub-systems. These sub-systems can be modeled as a mathematical function.
In Modelica a simple physical model is built in the respective software. From here all the properties of the system will be simulated and the result of the system can be observed and examined. This activity can save a lot of design process time especially in the embodiment and detail design phase. This will be a cost saving activity as fewer prototypes are required to be built.
The utilization of object-oriented programming techniques has given a benefit to the system modeling process. In our opinion this technique offers advantages over conventional functions structures. Function structures are proposed by several mechanical engineering schools [e.g., Altschuller 1984, Ehrlenspiel 2006, Pahl&Beitz 2004, Stetter et al. 2001]. These structures require high commitment and capabilities to model systems flawlessly and in a sensible, useful manner. Furthermore these function structures are in general not understood by electronic and software engineers. The application of UML diagrams can offer advantages as the rules are less rigid and as they are commonly known to electronics and software engineers. With this in mind a combination of the UML modeling technique and Modelica can offer a slight advantage in the process of modeling the system and especially in simulation processes.

5. Conclusions

In the described project a mechatronical product – a brake for a mobile robot – was developed. The mechanism in this brake is based on the application of a ferromagnetic shape memory alloy (FSMA) and has the capability to compensate wear and tear. This capability is very important because the strain which can be produced by a ferromagnetic shape memory alloy (FSMA) is limited. Tear and wear would result in reduced brake moments if no compensation possibility would be available.
In this exemplary development process of a mechatronical product project the application of object-oriented programming techniques especially UML diagrams was tested. The general applicability of some of the diagrams turned out to be possible in all domains of a mechatronical product, but requires refinement and additions. Appropriate UML diagrams were chosen and the definition of their components was adapted in order to be able to model the mechanical subsystems of a mechatronical product as well. However a further adaptation effort of UML diagrams is required to ensure all diagrams being applicable for other engineering domains. Up to now the result obtained in this research is only based on the analysis during the described project. Further research is required to ensure the validation and the general applicability. Right now further projects concerning the mobile robot are carried out to support the hypotheses and for further improvement.

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