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Application of Mechatronical CAD in the Product Development Process

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ABSTRACT

This paper is concerned with the design process of mechatronic systems. Synergies and integration in design set a mechatronic system apart from a traditional, multi-disciplinary system. The increased complexity of mechatronic systems, resulting from the beneficial interaction of components from various domains, requests the use of an appropriate design methodology. Computer integration and transparency of the product model data play an increasing role during the whole product life cycle including the process of product development. Coupling of modeling and simulation tools from the different areas of mechatronics in a so called "Mechatronical CAD"-system is one of the important points to decrease the time of product development.

Keywords: mechatronical CAD, conceptual design, product development process, integration.
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1. INTRODUCTION

Within the frame of this paper, the computer-aided product development process is discussed and analyzed from a mechatronic point of view. Mechatronics can be considered to be an integrative discipline utilizing the technologies of mechanical engineering, electrical engineering/electronics and information technology in order to provide enhanced products, processes and systems. Some typical examples are a state of the art video camera, a digitally programmed milling machine or a mobile phone.

In a mechatronic design process especially the phase of conceptual design is crucial. Here the functional interactions between domain-specific subsystems are determined and have to be investigated carefully therefore. This implies that during the phases of conceptual and preliminary design the designer should be able to quickly and accurately evaluate the system performance due to design changes in the mechanical part as well as in the other parts (electronics, software etc.). Successful development of complex mechatronic systems is only possible in close cooperation between specialists of the different domains (disciplines) involved. So the design activities take place in a multidisciplinary environment, which often involves engineers and other experts of different backgrounds. In order to push the performance of new products, the beneficial interaction between different fields (domains) of mechatronics is used more and more, which results in increased complexity of the products, because the mere combination of domain oriented partial solutions in general will not provide the optimum result of the integrated system (see [4], [7], [10], [13]).

2. MECHTRONIC DESIGN

Mechatronic design of machines, devices and plants can help to create improved and enhanced products, processes and systems. On the other hand, the complexity of these systems usually is

increased due to the intended beneficial interaction between components and technologies from different mechatronic domains (disciplines).
Therefore new concepts are requested in order to assist mechatronic design engineers in handling the increased complexity of such systems and in reacting faster to market demands. The paper deals with the description of the design process and product models especially for mechatronic systems and is intended to contribute to adequate structuring and evaluation of product design processes and product models in order to keep control over them and to make them more transparent.

2.1 Mechatronic Design Process

We treat (mechatronic) design as an iterative process of synthesis, analysis and evaluation. One crucial step in the design process is synthesizing design concepts according to requirements and specifications. In the following analysis step, properties and performance of a specific design concept or of a detailed solution are predicted. In the evaluation step, the derived performance is compared with the requirements. The design and even the requirements may be modified taking into account the new information obtained from the evaluation step. The process is repeated until a satisfactory solution is achieved (Fig. 1).

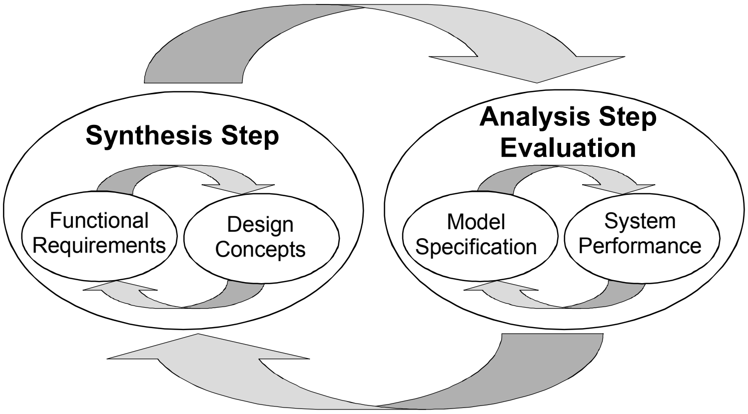

Fig. 1: Synthesis and analysis steps.

During the last years the evolution of market demands and product development tools have deeply transformed the designer's way of thinking and operating in the course of all the product development stages. In order to push the performance of new products, the beneficial interaction between different fields of mechatronics is used more and more on the one hand, but results in increased complexity of the products on the other hand. A lot of examples, such as ABS, drive by wire, brake by wire etc., are available from the automotive industry (see e.g. [11], [14]). Hence, a new adequate approach in design and engineering of mechatronic products can be considered as a key point to optimize the design process itself. Such approaches should help to better handle the increasing complexity and to assist in decision-making during the product design process which starts with conceptual design and is followed by basic and detailed design. Functional design combines requirements, functions and design parameters and plays therefore a central role in ensuring design quality and product innovation.

2.2 Computer Support in the Product Development Process

The enlarged use of computers, electronics and their continuous enhancement lead to increasing complexity of the product design process itself [10]. This paper is devoted to the task of finding an appropriate structure of a mechatronic system in combination with estimating its complexity by computer-aided support. Specific design tools are requested to support the engineer in solving mechatronic design tasks with their specific properties being in particular:

- The functional interaction between domain-specific (discipline-specific) components is the key of any mechatronic solution and has to be considered seriously therefore.

- The selection or alteration of a solution in one domain may affect the solutions in other domains.
- The prediction and evaluation of the system performance of a particular solution implies the investigation of the system components from different domains (disciplines) as well as their interactions. This makes it difficult to guarantee the specific performance of a new mechatronic system in advance.

One of the key-issues in the development of modern mechatronic systems is the strict integration of mechanical, control, electrical and electronic aspects from the beginning of the earliest design phases on, as it can be seen from Figure 2.

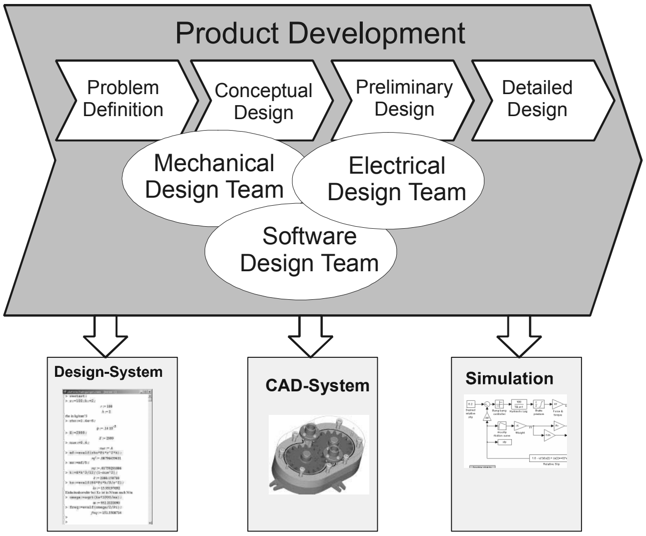

Fig. 2: Computer-aided tools in mechatronical product development process.

2.3 Conceptual Design Stage

The determination of the product's overall function, of its most important sub-functions (main functions) and their interactions lead to a functional structure. During this design phase, principle solutions with a structure of realizable modules should be established. This structure including the modules and their couplings (interactions, interfaces) is essential for the following design steps and hence for any product model used in the CAx-systems involved. A well chosen structure facilitates Systematic Design as well as Simultaneous Engineering.

For the main functions, solution principles, making use of physical, chemical or other effects are established. These solution principles can be combined to one or more basic (principal) solutions for the overall product. The utilization and proper combination of solution principles from different mechatronic domains allow for an extended variety and quality of principal solutions. After the selection of the best realizations of principal solutions or their best combinations respectively, the modules have to be conceptually designed. This means that the main parameters of these modules have to be fixed or at least the rules for their definition have to be established.

The term modularity has been widely used in different contexts, ranging from manufacturing to the design of electrical and mechanical products and software. To achieve the defined life cycle engineering objectives through modular design, the relationships between the objectives and the modules should be established. As product functions are realized by physical structures, the relationships between functions and physical solutions should also be determined. Essentially, modular design decomposes a product or groups components into separate modules.

2.4 Mechatronic Design Models

Today fast product development, high quality level, minimum environmental impact and the minimum level of costs have become essential demands during the whole life cycle of the product. To minimize the number of iterations during the engineering process, it is necessary e.g. for the mechanical engineer to consider the possibilities of automatic control when dimensioning the plant. This results in a modification of the traditional design process. For the achievement of all aspects, discussed in the previous chapters, we need a method, which helps the engineer to analyze and evaluate functional requirements and design parameters of possible solutions. Our mechatronic pillar design model was developed to assist the engineer especially in mechatronic design tasks by structuring of the design process and by increasing transparency.

A mechatronic module [5] utilizes several disciplines of mechatronics (e.g. mechanics, automatic control techniques etc.). In such a mechatronic module exclusively domain-specific components are merged. That means, a mechatronic module can be decomposed only into domain-specific (non-mechatronic) components, but not into other mechatronic modules or mechatronic system components. A mechatronic module therefore designates a mechatronic sub-system at the lowest hierarchical level of a mechatronic system and is indivisible within the set of mechatronic sub-systems. With the mechatronic pillar design model (see [5], [6]) all couplings between the several mechatronic disciplines (domain pillars) can be described in a superior data platform (Fig. 3). Each model pillar characterizes a domain-specific sub-component, which is structured into several hierarchical levels corresponding to the proceeding degree of detailing. Thus only the first (highest) level has an interface to the other pillars (compare with object-oriented programming) via the mechatronic coupling level. All couplings between the model pillars (e.g. design parameters and requirement parameters, who affect multiple disciplines) are captured and described at the mechatronic coupling level. The model structure has to be adapted if additional couplings between domain-specific components are detected during a design iteration (design, analysis, integration, performance check etc.). This is also true if new or additional domains (pillars in the model) come into consideration.

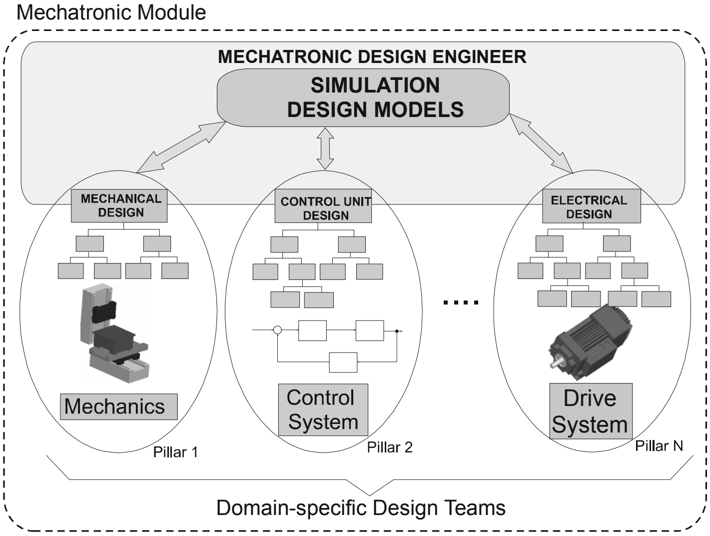

Fig. 3: Mechatronic module.

3. PRODUCT MODEL

Computer support and product models are well established for the process of embodiment design, the early phases of product development, such as conceptual design, even nowadays often are carried out isolatedly from the subsequent phases. For the evaluation method, which is discussed in this paper, we realised a computer aided tool, able to evaluate the structure of different design concepts. By computer aided hierarchical structuring and modularisation of the components, the complexity of the different solution concepts can be analysed very quickly. Additionally, more transparency is obtained when studying the effects of modifications and adaptations at an existing mechatronic concept.

3.1 Product Model Data Exchange

A computer-aided software tool that can do all the different simulations needed in virtual prototyping process does not exist. That is way connections between different software packets are needed. Packets have to have transformation modules that can convert between different representations and file formats used in different simulation programs and CAD-programs. Possibility to connect user defined function libraries to simulation program is very important. Testing of the actual mechatronic machine modules with help of the simulator is also possible if the simulator supports low level connection to networks so that control can be send to machine controllers and machine sensor data can be directed to simulation software.

Coupling of modeling and simulation tools from the different areas of mechatronics is one of the most important points to decrease the time of product development. CAx-systems were developed to a large extent to optimally perform specific tasks. CAD was originally developed to define the geometry of a part, CAM to define the manufacturing process, CAE/FEM for analysis and evaluation of product properties. The data generated and applied by these different systems are mutually coupled, therefore efficient data exchange and interaction between the CAx-systems involved is a key-point in today's innovation processes (Fig. 4). In this context it is necessary to describe the complex structure and hierarchy of the product, which finally allows the use of product data management functions for simultaneous engineering. The calculation and simulation tools, which are used in the product development process, can be classified into three categories according to the different design stages, namely tools for dimensioning, verification and optimization.

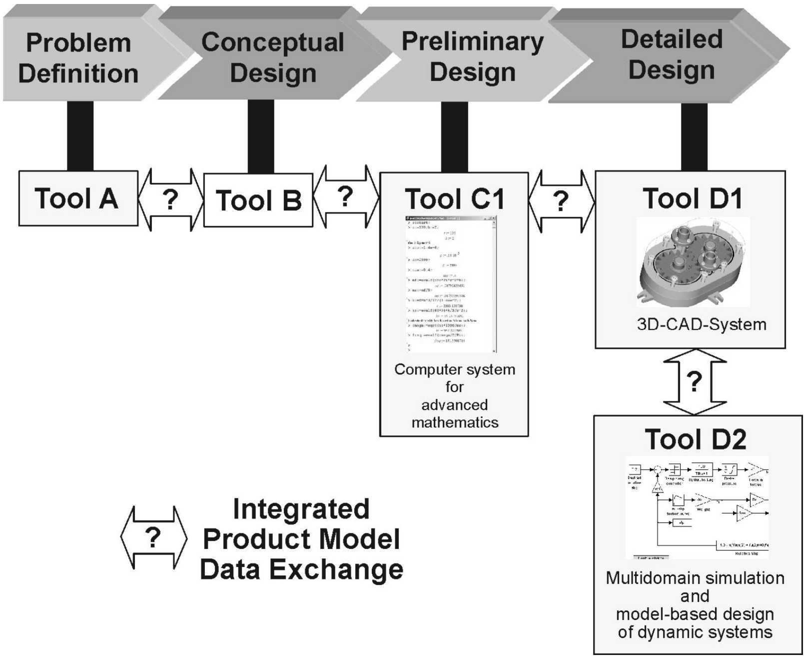

Fig. 4: Product model data exchange.

3.2 Design Model Parameter

On the basis of the traditional approaches for the developing and designing technical systems (e.g. VDI guidelines) strong changes in the design process appeared in the last years, which are affected particularly by the intensified computer application, as well as by the rising efficiency of these programs. This requires a reorientation of the design engineer, since the proceeding is nevertheless entirely different from the non-parametric function ([1], [2], [4], [8]). The design engineer has to himself with the parametric construction before the beginning of the work a reasonable concept (design rules) for dependence. It can come later by the definition of new variants to perfectly unwanted results, if the parametric is not meaningfully developed.

A central question participates, how far a parameterizing of a model is meaningful. It is conceivable, that to a certain point (degree of detailing) of the development process parameterizing is dissolved and by fixed values is replaced, since it means a large expenditure to parameterize a system in the last detail completely. Exactly this choice of the transition from a parametric description of model to a detailing by selection from fixed components (modules) represents a possibility of adapting expenditure and description of a task of development to the requirements. If this transition in a too early phase takes place, then larger difficulties exist to accomplish these model-supported efficiently when subsequent changes. It is recognizable that functionality rises closely and with it connected the complexity of technical products, if different disciplines of the mechatronics are involved. For the handling and computer aid of the development process product models represent an important basis. Thus more rapid generating of copies and variants, as well as a simpler modification of constructions is possible. This does not only require an increase of the use of computer-aided systems, but also their integration, so that data exchange can run loss-free, sources of error avoided and will faster go through optimization cycles.
It must be ensured by the description of model that the gradual development of the integrated product model from an abstract specification to a detailed is possible. The design methods must not only after time become evaluated and to cost saving, but also the quality insurance plays an essential role during development process. In this respect the important criteria leave themselves as comprehensibleness of the method of the solution identification, provision of the decision criteria, standardized operational consecution of development process, definition of criteria and characteristics for the individual giving full details and step question. This contribution deals with the central questions of as simple as possible description and documentation of a parametric design model, because the potentials of parametric 3D-CAD-systems and the computer integration is not at present used complete. At present there exists only a few utilities fur structuring and administration of the parameters. A further aspect treats the tendency that the parameters of the geometrical design not only linked to be, but also the parameters of the design of other disciplines, if it is in the development process of mechatronic systems.

4. COMPUTER AIDED CONCEPTUAL DESIGN TOOL (MECHATRONICAL CAD)

Computer integration and consistency of product model data play an increasing role during the whole product life cycle including the process of product development. One of the main functions we need in the mechatronic design process is to manage the enormous amount of data generated by the several domains and their interaction.
Whereas computer support and product models are well established for the process of embodiment design, the early phases of product development, such as conceptual design, even nowadays often are carried out isolated from the subsequent phases.
The aims of computer aid in the conceptual design phases are:

- to force the engineer to design in a systematic manner
- to evaluate and compare a higher number of different promising solutions fast enough
- to provide support for the documentation of the design work
- to release the team from routine work
- to give good preparation for the subsequent detailed design
- to support standardization

Mechatronic systems are from their nature dynamical systems. For computer assistance already during the early phases of design, consequently an adequate software tool has to fulfill two main requirements [15]:

- representation of the system's functional structure
- possibility of dynamical simulation and analysis of the total system

The physical behavior of a technical system depends on the properties of the subsystems and their physical interaction. The interactions between subsystems take place at interfaces - here an interface is viewed as a relationship between a pair of mating features. Product models are important containers of characteristic product properties such as shape and material. With the assistance of present state-of-the-art computer-aided engineering technology, finite element and multi-body systems, modeling of geometric objects is a relatively straightforward technique. In contrast to this, proper modeling of all the different interactions inside a mechatronic system is not straightforward. Furthermore, management of interface objects and different representations of such objects is not addressed by information models in present software tools for computer-aided design and product life-cycle management.

4.1 Requirements for Mechatronical CAD

In a computer-aided tool for mechatronic design we should parameterize the whole problem and not just a part of it even in one discipline. The parameterization has to be consistent for all disciplines and models involved. The handling of complex models must be possible through all iterations of the design process. Furthermore, it should be possible to integrate this approach into existing applications.
For the design method, we realize a computer aided tool, able to handle different design concepts and to determine the best solution for further detailing. The main requirements are

- Computer aided hierarchical structuring and modularization of the components;
- Development environment with convenient graphical user interface;
- Specification of data exchange between the several modules.

4.2 Implementation

A universal development tool able to perform all the different synthesis and analysis steps needed in the mechatronic development process does not exist up to now. Thus connections between different software tools are needed. A development platform has to guarantee that mechatronic modules together with the necessary different views and models of these modules can be handled. In the platform we can switch between different representations (models) and file formats used in different simulation- and CAD-programs. Also the possibility to connect external sources and user defined function libraries to the program is very important in order to allow for extensions of the platform.
For the realization of a first prototype of such mechatronic development tools we use one of the basic principles: “Effective programming means to make use of well established software as much as possible”. In Fig. 5 we can see this implementation of a mechatronic development platform for example with high-level technical computing software MATLAB™ [9] and 3D-CAD-software Pro\ENGINEER™ [12]. The main item is the “Mechatronicical CAD”, in which the coupling parameters between the domains are described and the interactions are analyzed. A graphical user interface allows the designer to handle the conceptual design model by an easy to use interface. The simulation of the couplings is accomplished via the software module MATLAB\SIMULINK™. The couplings can be described by functional, logical and procedural operations. Therefore a communication between MATLAB™ and a 3D-CAD-software is necessary. The coupling parameters can be exported to the CAD-system, where the parametric geometric model is created. When the CAD-system regenerates a design model with the aid of the list of parameters, it recreates the model feature by feature in the same sequence in which each feature was created and in accordance to the hierarchy of the parent-child relationships between the features. Now the mechanical properties of the model can be evaluated and at least these characteristics of the model can be transferred to a model for the controlled system for the purposes of controller design. Data exchange between MATLAB and the 3D-CAD-system can be executed in both directions at any time, but in the moment of exchange it is only unidirectional. So we can speak of sequential bidirectional coupling. After each data transfer the next detailing step of the model in the domain specific discipline will be elaborated.

5. APPLICATION

5.1 Three-Axis Milling Machine

In the first case study the implications and effects of two different system structures are analysed. A milling machine is a power-driven machine used for complex shaping operations of metal parts. The basic form consists of a worktable for a workpiece and a rotating cutter which rotates concentrically to the spindle axis. The two parts have to perform three-dimensional motions relative to each other. Milling machines may be operated manually or under computer numerical control.
The basic layout of a 3-axis machine tool structure consists of an open serial chain of four mechatronic modules, the spindle (S), the X-axis (X), the Y-axis (Y), the Z-axis (Z) and the table with the clamping devices (T). Figure 10 shows two of the several possibilities for the arrangement of the modules.

The mechatronic modules themselves in both arrangements are identical. In the following table, the determination of the product complexity of the overall machine is presented.

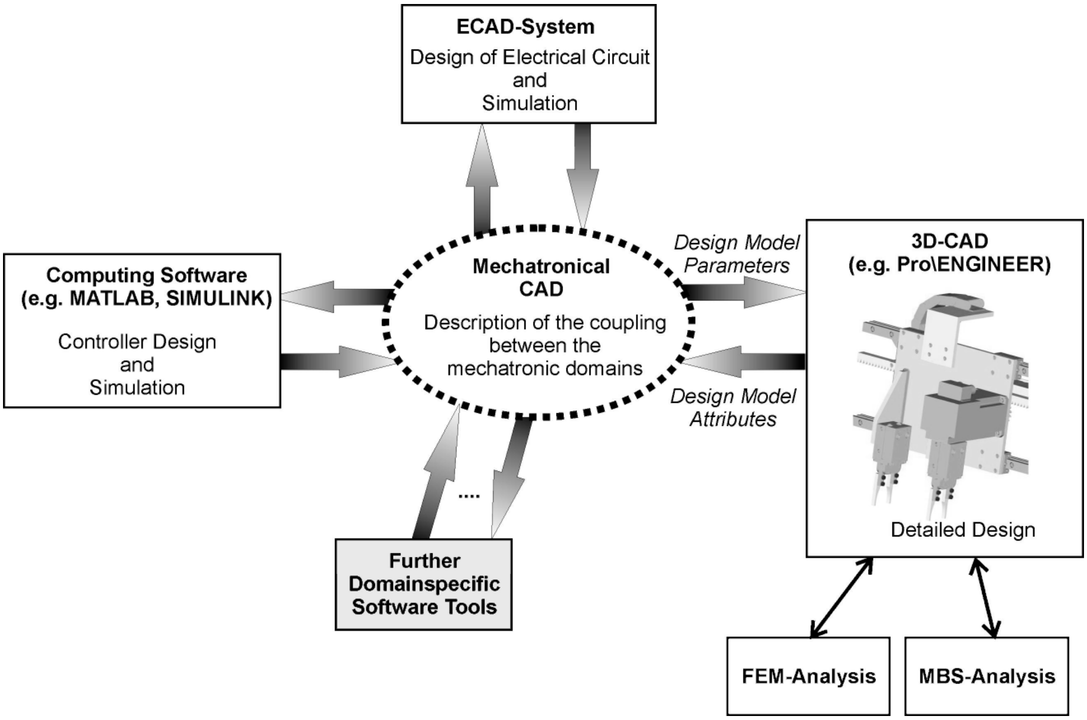

Fig. 5: Computer aided conceptual design tool.

In this simplified case study a typical problem may be recognised, namely, how to arrange modules to different structures. Arrangement 1 has lower design complexity than variant 2, although the same modules are used. The different mechatronic modules are described by their complexity. The higher complexity of variant 2 can be interpreted by deeper integration of more hierarchical levels.

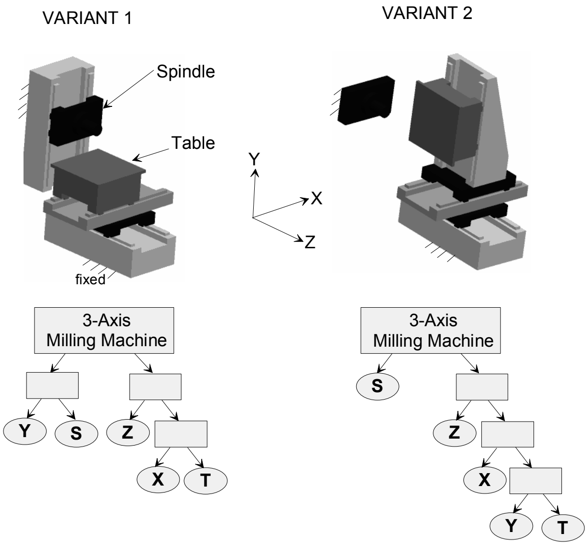

Fig. 6: Milling machines.

The determination of product complexity, shown in Table 1, helps the design engineer to find the promising solution concept. With this selection the step of preliminary design is well prepared. Modern 3D-CAD-systems offer the possibility to elaborate preliminary design and detailed design with computer aid in one system.
The complex functions and possibilities for optimization of modern 3D-CAD-systems allow further to regard the following aspects of design a milling machine. The determination of the volume and mass of the components is a standard function in every CAD-system. One important simulation is the calculation of the displacements und stress the milling machine tool subjected to cutting forces. Also dynamic analyses help to determine the first modal frequencies. With this extended information the design decisions can be made more exactly.

	Mechatronic Modules				
	X	Y	Z	T	S
$PC_{mechatronic\ module}$	0,5	0,2	0,6	0,2	0,4

$PC_{mechatronic\ system}$	variant 1	**6,4**
	variant 2	**6,6**

Tab. 1: Example of product complexity of two different mechatronic systems.

5.2. Clamping Device
The positioning and configuration of clamping devices used in various machines or stations of a production line for car bodies is a current question from automotive engineering. Clamping devices have the job to fix different sheet metal parts quickly to one another at an exact position and with a pre-defined clamping force. After the parts are fixed, they are joined together e.g. by welding. The criteria for such clamping units are:

- Compact size of clamping device
- Flexibility in use and operation
- Closing speed
- Number of cycles
- High reproducibility
- Accessibility for (spot) welders

In Figure 7 we can see two sheet metal components to be welded together. In order to keep the parts in the correct position, they are clamped between a fixed abutment and a movable element (closing element) with two clamping jaws. For quality assurance it makes sense to measure the clamping force in order to detect deviations from the ideal geometry. This can be done by additional sensors (e.g. strain gages, pressure sensors) or by analyzing system variables (e.g. electric current, air pressure) from the drive unit. According to the mechatronic pillar model we decompose this design problem into three domain-specific components and their hierarchical levels. The different model pillars are shown in Figure 8. One pillar characterizes the mechanical components, such as material, geometric dimensions and kinematics of the parts. At the different levels of detailing we can see requirements for assembling, manufacturing etc. The second pillar represents the drive unit (e.g. electric, pneumatic or hydraulic) with the supply unit. And the last pillar is dedicated to measurement techniques.
At the mechatronic coupling level, all specific design parameters (type of drive, length of clamping lever, clamping and holding torque) describing the couplings between the several domains are collected. The requirements to the mechatronic design problem are the desired clamping and holding forces. If - due to a new requirement - the clamping force should be controlled, we can simply extend the mechatronic pillar model with a domain-specific component for suitable controllers. In order to clamp complex sheet metal parts, it is necessary to use several clamping devices. All of them represent mechatronic modules, which are combined through their positions on the parts. Naturally, it is impossible to produce a welded structure of good quality (in agreement with the geometrical tolerances for the welded assembly), if one or more of the clamping devices are displaced from their correct positions or the geometric deviations of the incoming sheet metal parts are too high. Detecting geometric deviations is possible by measuring the clamping forces at each clamping device and evaluating them in an integrated software module.

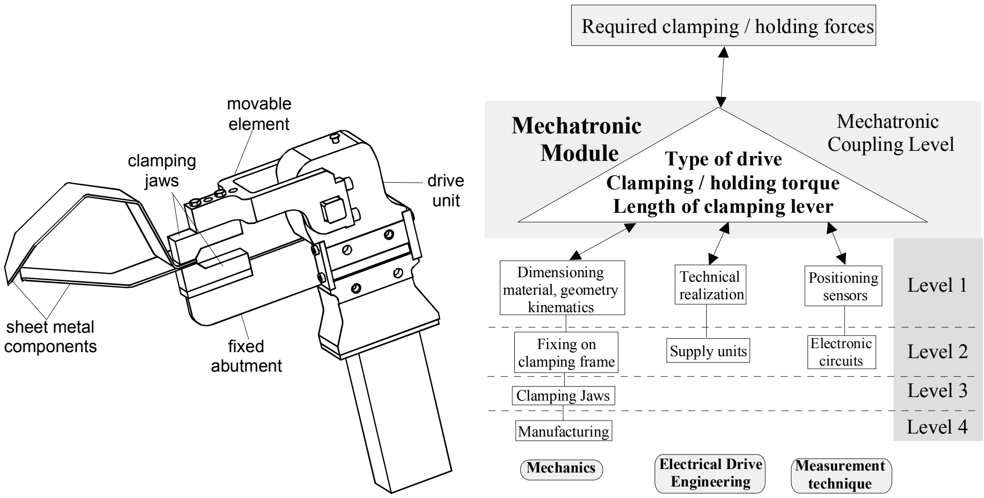

Fig. 7: Hierarchical design model of a clamping device.

6. CONCLUSION

With the usage of the design tool (Mechatronical CAD), we have a universal data model also for the early stages of mechatronic design processes. Hence, a model database is available, which describes the overall mechatronic system. It is warranted by this structure of the model, that modifications can be carried out very quickly and efficiently. The development methods and tools, presented in this paper, are a first step to assist the engineer in the conceptual design process. In the next step, we want to realise an implementation which is independent of a specific software-tool such as Matlab Simulink and at the same time open for other CAD-tools.

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