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DESIGN MODELS IN THE DEVELOPMENT OF MECHATRONIC PRODUCTS

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Abstract: *In view of widespread application of mechatronic systems and the competition to offer customized products at high quality and low cost, there has been considerable attention to introduce new methods and models in this regard.*
This paper explores design process of mechatronic product development with the aid of models. The role of software not only as part of the product but also in the development process. These models contribute to product structuring and evaluation of design process by reducing the complexity and their use for product customization.
Key Words: ***Mechatronic Product Development Process, Design Models, Design Complexity, Modular Design, Mass Customization***

1. INTRODUCTION

In mechatronics, the interconnection of technologies through functional and spatial integration is adapted to create improved and enhanced products, processes and systems. But the consequence is that the complexity of these systems is usually increased due to the intended beneficial interaction between components and technologies from different mechatronic domains [1]. The design of mechatronic system requires a systematic development and use of design tools. In addition to domain specific engineering such as (mechanical, electrical/electronic, information technology and user interface) an integrated, concurrent engineering approach is required. Such an approach makes a mechatronic design more complex but on the other hand also more optimal than a conventional approach [2][3][4].

The term complexity defined as the interconnectedness and the degree of organization of a system or in other words a *whole composed of interconnected parts* [6]. How complex the system is: depends on the intricacy of the relations among its elements and disciplines, and the number of elements involved (i.e. size) [19]. Complexity is a problem due to integration of functions, solution elements and technologies as well as the required interaction between various tools, data exchange and designers in the design of mechatronic systems. The benefits of adopting complexity in design are products with enhanced performance, improvement in their behavior and increased functionalities.

Mass customization (MC) has been recognized as a successful approach in the design and development of products tailored to customer needs. One of the concepts of MC is modularization. Modularization is a structuring concept, which enhances clarity, reduces complexity and increases flexibility for customization [26]. MC and modularization may be applied to mechatronic products, which are becoming more and more important as a product type. Furthermore, the principles of mechatronics can be utilized to achieve efficient product customization, since customization can be implemented in software rather than physical components enabling postponement of differentiation point and generally reducing the variety of components.

In general ,the challenges and their solutions in some cases identified by academic research and industry during the design and development of *mechatronic products or systems are*: exchange of design models and data [7][10], cooperation and communication among the design engineers [1][7][9][10][12][13], multi-disciplinary modeling [8][11][12], simultaneous consideration of designs from different disciplines [8][9][11][14], early testing and verification [9][11][12] ,persistence of a sequential design process [7][8][13], lack of tools and methods supporting multi-disciplinary design [7][8][9][14], support of the design of control software [2][9]. With these challenges, four core issues are identified which influence the problems in the development of mechatronic systems, these issues mainly relate to *design integration, design verification, communication among designers and generation of control software.*

Therefore, further concepts and models are *required* to assist the design process, such as the use of software tools for analysis and design verification, generation of control software as well as concurrent design of physical system and its control and MC approaches such as modularity to reduce complexity.

The objective of this paper is to discuss design process and generate models in order to contribute the required structuring and evaluation of mechatronic product development processes. Reducing complexity in the process of developing mass customization products can be achieved by modular design. An additional objective is to describe the significance of software tools and their use for achieving design integration, verification and generation of control software. The research questions in this paper are: *1)How can design models help structuring of the design process and reduce complexity in development process of mechatronic systemss?2)How can software tools be used for design integration and verification? 3) How can modularity reduce complexity in the development process of mechatronic systems?*

2. METHODS

In this paper new design Models and methods are developed to achieve the required structuring and evaluation of the mechatronic product development process. In these models, the design process/steps at different levels of development are elaborated in relation to mass customization. An example is discussed especially at the modeling and simulation phase of development to answer the core issues related to complexity such as design *integration, design verification, communication among designers and generation of control software*. Models of the mechatronic system functional and structural views are developed. A case of mechatronic module is developed with domain specific details.

3. MECHATRONIC PRODUCT DEVELOPMENT PROCESS

The design and development of mechatronic systems require the aspects of cooperation among different domains, how to handle greater complexity and use of virtual prototyping through modeling and simulations. Mechatronics offers potential for success in products but at the same time need special requirements on the development process especially at the initial development phase due to the integration of various domains, posing a high level of complexity. Since the interaction between mechanical, electronic and information processing components influences the behavior and form of the overall mechatronic system, design models and methods are used at different levels of the development process.

3.1. V-model

A guide for a basic development process is offered by the V-model and adopted to the requirements of mechatronics; it describes the logical sequence of important sub steps in the development of mechatronic systems [18]. In systems engineering, the V-model is used as a standard model for the development of complex systems [15]. In order to further clarify the *system design*, the V-model is modified by adding the design steps at various stages; these steps are used in subsequent models to identify the design steps along the development process as shown in figure1.

The V-model consists of *system design phase, decomposition phase and the integration and verification/validation phase.* System design is a process where system specifications derived from user needs are transformed into component level specifications by defining subsystems and components. This is the conceptual design process, where the determination of the product overall function, of its most important sub functions and their interaction lead to a functional structure. Then modeling and simulation is performed and structural and behavior models (e.g. physical model, mathematical and numerical models etc) are formed. In case of mechatronic systems, the components at the lowest level are composed from mechanics, electronics and control software modules. At the detailed design, domain specific modules are developed further on the basis of established domain specific development methodologies. At the system integration phase all the functions, components and the subsystems are combined, and then verified as well as validated in an iterative process to the requirements and system specifications.

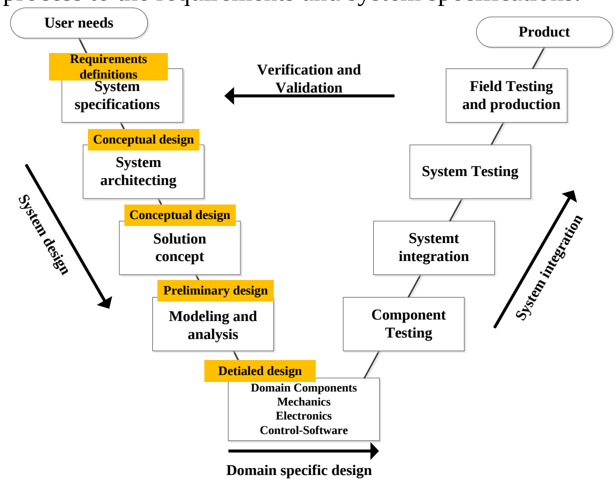

Fig. 1. V-model for mechatronic product development [modified from VDI 2206].

In general, mechatronic system design is an iterative process; system design is enriched by models towards preliminary design, along with analysis and simulations e.g. system is simulated along with control design to get the required response (see Fig 2).

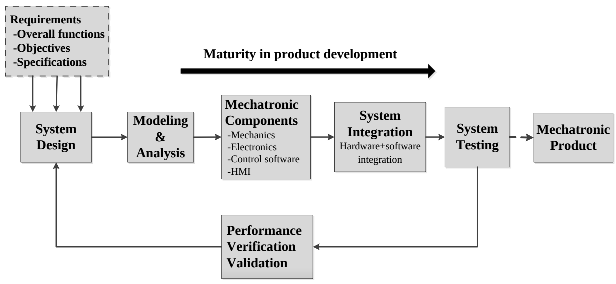

Fig.2. Model about the main steps elaborating the systematic design and development of mechatronic products.

The domain specific components i.e. mechanic, electronic and control software are further developed in detailed design and finally all components of the systems are integrated and tested against requirements.

3.2. Conceptual design

The Function-Behavior-State (FBS) modeling [16] supports systematic modeling and reasoning in conceptual design. The method symbolically represents such concepts as function, behavior, state, and relations among them. Conceptual design using the FBS modeling is performed through development (decomposition) of functional requirements (i.e., function modeling [17]), and definition of symbolic behavioral and structural descriptions (physical phenomena) to realize functions.

Modeling and design are going hand in hand in an iterative manner. In the beginning, the design is enriched by having some information about the system (e.g., intended functions, requirements, problem definition, performance specifications, past experience, and knowledge of related systems) and using the design objectives, it will be possible to develop a model of sufficient (low to moderate) detail and complexity. By analyzing and carrying out computations through software tools (for its behavior and structural domains of the FBS model) it is be possible to generate useful information that will guide the design process (e.g., generation of a preliminary design). In this way, design decisions can be made and the model can be refined using the available (improved) design. This iterative link between modeling and design is schematically shown in the following figure.

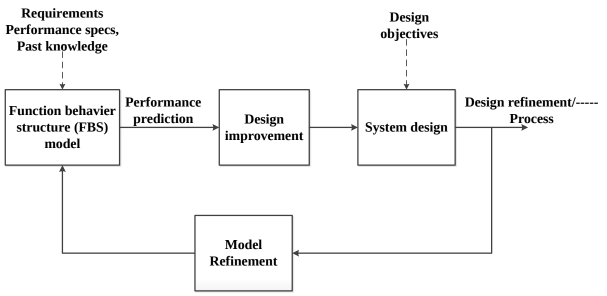

Fig.3. Link between modeling and design at conceptual design phase.

4. ROLE OF COMPUTER AIDED DESIGN IN MECHATRONIC PRODUCT DEVELOPMENT

A computer aided software tool that can do all different modeling and simulations needed in virtual prototyping process does not exist. Coupling of modeling and simulation tools from different areas of mechatronics is one of the most important points to decrease the time of the product development [1]. Additionally, reducing the complexity by combining all the parts at the beginning of the design in a virtual environment is not only to get the desired response but also to reduce the time and cost of the mechatronic system development.

Because of the many varieties of designs, the modeling and simulation plays an important role, as well as reducing the number of physical prototypes. Therefore, modeling of the heterogeneous components is required, using general modeling principles. At the *system design stage* of development, use is made of software-in the-loop simulation (SiL), such that components and control algorithms are simulated on an arbitrary computer without real-time requirements to obtain, design specifications, dynamic requirements and performance measures [5]. At the *detailed design*, domain specific tools such as ECAD for design of electrical circuit and simulation, various software tools e.g. Matlab/Simulink for controller design and simulation, 3-D CAD tools e.g. Pro Engineer and CATIA for detailed parts and geometry, CAE/FEM for analysis and evaluation of product properties are being used, as shown in figure 4.

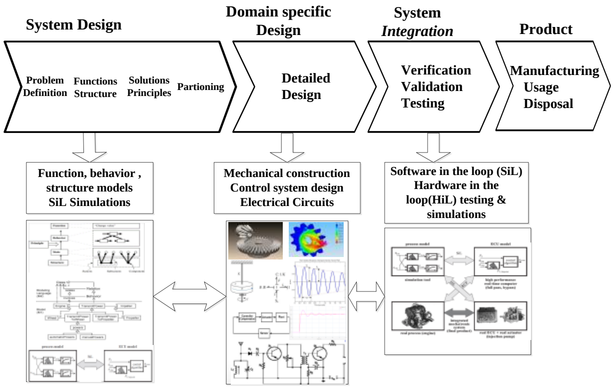

Fig.4. Model about software role during mechatronic product development process.

Mechanical, electrical and software domains cannot be developed independently from each other at the beginning of the earliest design phases. Integrated, virtual and mathematical models are developed (Fig 5) as they are less time consuming and are less expensive than physical prototypes.

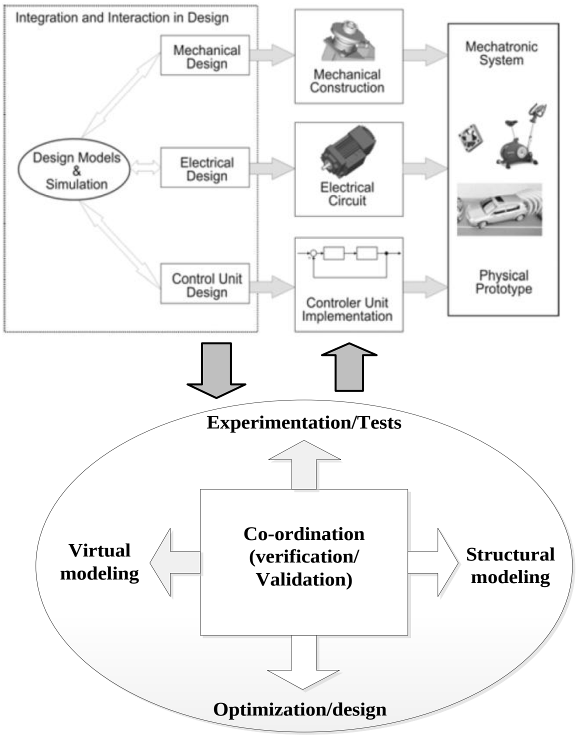

Fig.5.Virtual prototyping through modeling and simulations and their coordination during mechatronic product development process. (First figure from [30]).

4.1. An example of virtual protopyping at system design

Modeling and simulation is advantageous in the development of mechatronic systems. Because of interactions and increasing complexity brought by coupling of electromechanical systems require modeling of the system behavior in the early design phase. For example interaction of motor with gears and their motion control in the example of antenna pedestal system (Fig 7) is modeled in *Bond graph (BG)*. It is also possible with software to analyze number of possible configurations (with respect to size) of the system without going for any physical prototypes.

This example is about an antenna pedestal system comprising electric and mechanic domains and their motion control system. Modeling the electric and mechanic parts separately will not give the optimal design; in order to get the overall response of the system; a graphical method such as BG is used. With the BG modeling, state equations representing the behavior of the system can be derived and can be easily simulated in software tools. In BG, the physical system is built with power bonds which represent the power distribution amongst the individual elements, while the control part follows signal flows. *Complexity* is reduced through BG, with the interaction of all the functional elements, flow of energy in the elements and generating the overall response of the system.

In a typical mechatronic system, the dynamic behavior of the process (plant) is controlled to achieve the desired response. Main /subsystems components of antenna pedestal which are interconnected through the flow of either *information or power* are shown in figure 6. The high power energy transfers are shown by half arrows, whereas the information transfers are shown by full arrows.

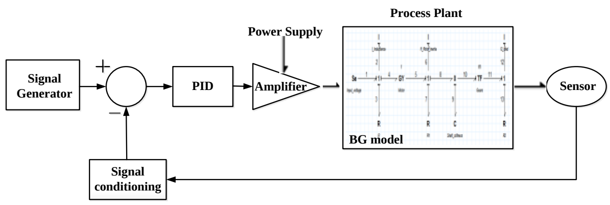

Fig.6. Schematic Model of Antenna pedestal system, with information and energy flows.

A complex system can be abstracted (i.e. reduce its complexity by emphasizing essential characteristics) from various points of view, for example, by Domain (e.g. the hydraulic system of an airplane -mechanical domain), by Flow (e.g. the autopilot control system – signal flow), by Function (e.g. the propulsion system – propulsion function) [19].The procedure for modeling may vary for different domains of mechatronics. In the domain of software technology, for example, the interrelationships between requirements for the system and the subsystems may be structured and represented in a functional description-on the basis of requirements analysis [20]. In order to describe the behavior with the required accuracy, substitute models of the system are formed on various abstraction levels [21] as shown in figure 7.

Models and Software tools reduce the complexity and development time, by not only integrating the domains of electric and mechanics with their interactions, but also by verifying the design models through simulations. In the antenna example (Fig.7) electromechanical and mathematical models is generated by BG that can be used for the generation of embedded software and for customization purposes.

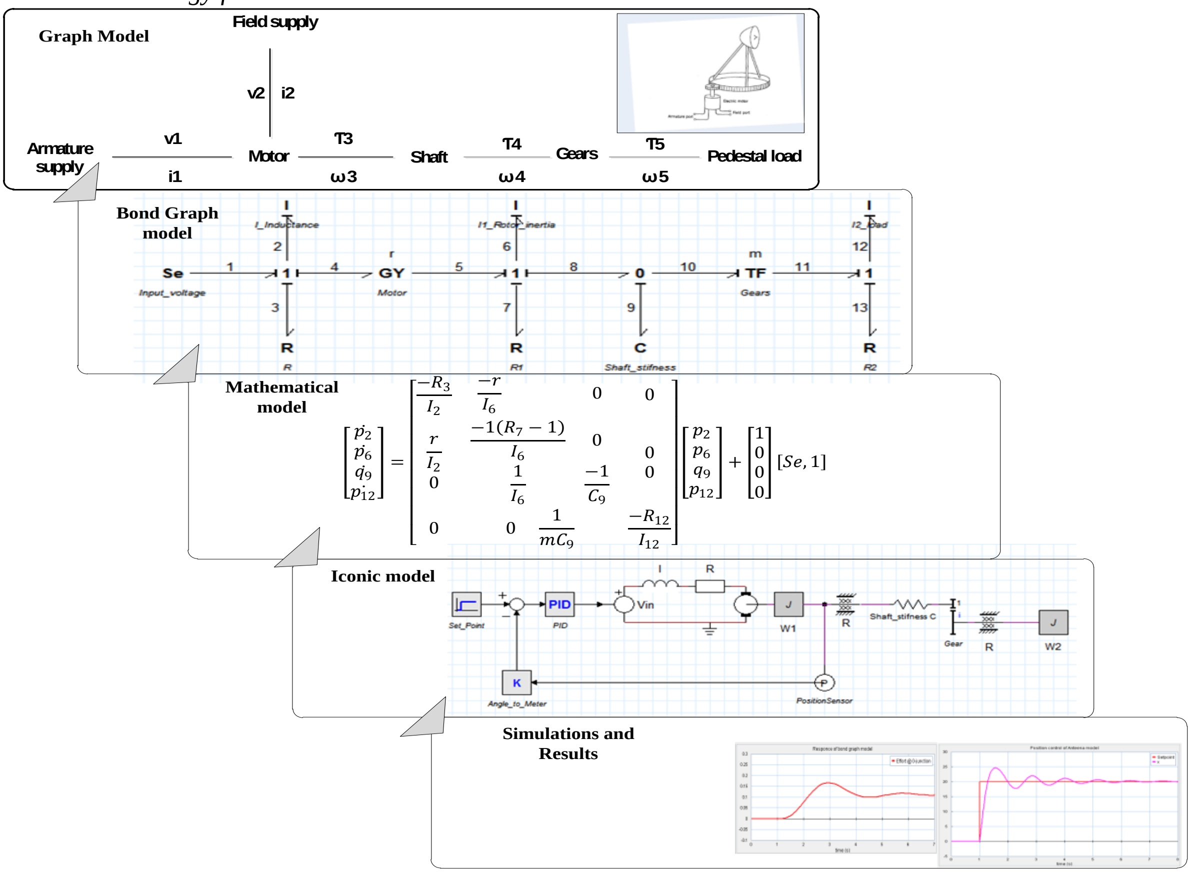

Fig.7. *Model abstraction levels for the development of Antenna drive system.*

5. MASS CUSTOMIZATION APPROACH TO REDUCE COMPLEXITY THROUGH MODULAR DESIGN

The aim of developing and using modules is partly to make it possible to create customized products for the market and partly to reduce the number of variants which have to be dealt with internally in the company, and thus to reduce complexity and cost [24]. Modularity is an attribute of a system related to structure and functionality. A modular structure is a structure consisting of self-contained, functional units (modules) with standardized interfaces and interactions in accordance with a system definition. Replacing one module with another is a way to develop a new variant of the product [25].The complexity of mechatronic products leads to a widened consideration of the system: the specification of functions cannot take place in isolation, as it can in the case of classic system technology. Even in the functional description, physical, geometrical and technological aspects must be taken into account. To deal with the complexity, methods such as modularization, hierarchization, portioning and integration are used [28] [29].

In mechatronic product development, one of the forms of integration is modular integration, where the overall system is made of modules of defined functionality and standardized dimensions in various size and classes. These modules that are included in modular system can be flexibly combined and make it possible to obtain great functional variety. Modularly integrated systems generally also have a larger component volume and higher material expenditure and component complexity in comparison to other forms of integration of systems [21].

Like for other types of products, modularization issues can furthermore be related to structural and functional views (Fig 8). The structural view of mechatronic products is primarily related to physical components and the functional view is primarily related to software.

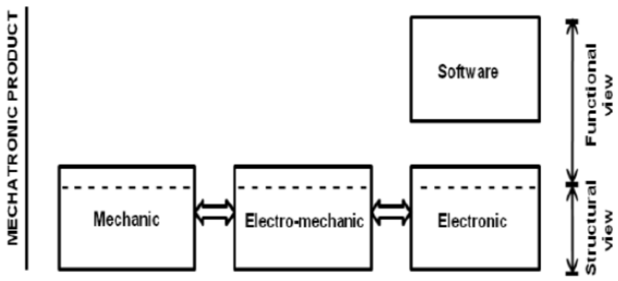

Fig.8.Simplified model of mechatronic products with structural and functional views [modified from 27].

A mechatronic module 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 (Fig 9). *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 [22], [23]) all couplings between the several mechatronic disciplines (domain pillars) can be described in a superior data platform. 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.

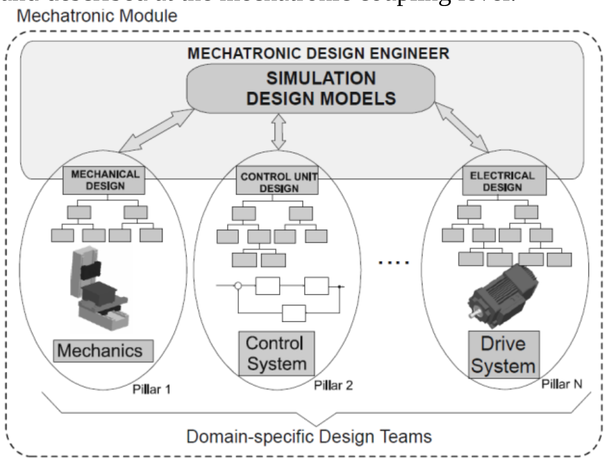

Fig.9. A model of mechatronic module [22].

Mass customization companies must benefit by using the modeling and simulation tools to analyze the product performance at system level and avoid the physical prototypes to accelerate the product development time and thus reduce the costs. After the desired response through (BG models, C code generation and real time implementation) it is also possible to generate a number of controllers with varying parameters of the individual elements representing the physical system. These controllers are basically software that can be used for customization in products or for delayed differentiation at customer site.

The structure of mechatronic systems generally consists of various mechatronic modules i.e. system elements and components which are combined to form a group and perform certain functions (Fig 10). Basic mechatronic module comprises sensors, actuators and information processing and is connected by means of material, energy and information flows. The module can be decomposed into only domain specific components i.e. mechanics, electronics and control software. If a number of mechatronic modules are coupled then a system of higher order is created with learning process and adaptation, where the mechatronic modules are coupled with information processing.

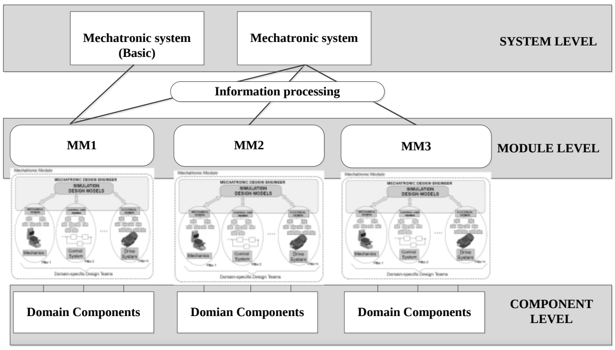

Fig.10. Model of the structure of mechatronic systems at three levels.

5.1. An example of mechatronic module development

After the behavior analysis through simulations, a mechatronic module is developed further into domain specific design. In the example of antenna system, *domains of mechanics, control unit and electrical system* are developed at multiple levels, for example *mechanic part* include materials, geometry, dynamics , gear system design, fixing drive unit with antenna and manufacturing details etc (Fig 11).

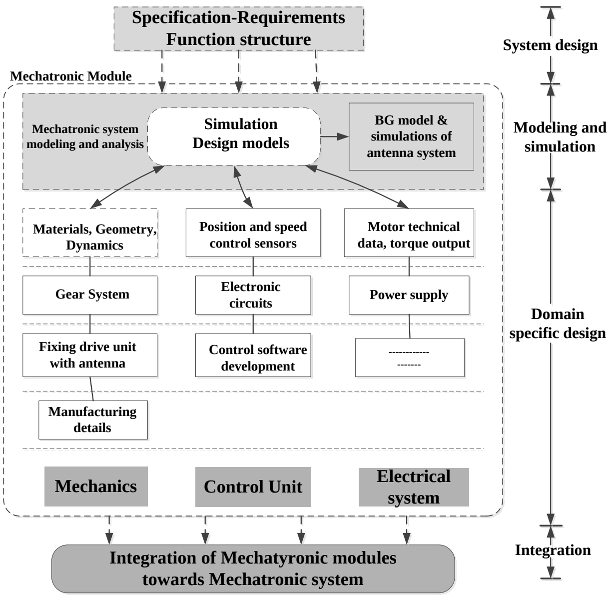

Fig.11. An example of mechatronic module development.

With respect to MC, the mechatronic modules comprising the *domains of mechanics, control unit and electrical system* are developed of defined functionality and standardized dimensions in various sizes. The modules included in a modular system can be flexibly combined and make it possible to obtain great functional variety.

6. DISCUSSION

The V-model is a guide adopted from software development and adapted to the requirements of mechatronics and describes the logical steps in the development of complex mechatronic products. Based on the V-model another model is developed illustrated in figure 2, describing the main steps in the development process, where the feedback from system testing to system design for the verification and validation purpose is shown and discussed as an iterative process. The intention is to make the design procedures more structured and elaborate at various stages/phase of design.

The FBS modeling supports systematic modeling and reasoning in conceptual design. In the beginning, the design is enriched by having some information about the system; it is possible to develop a model of sufficient (low to moderate) detail and complexity. At the conceptual design phase, a link between modeling and design is established, in order to refine and improve the model by analyzing and simulations through iterative process. This model guides the design process towards preliminary design.

The complexity inherited in mechatronic systems is primarily due to interactions and integration issues, is handled through BG method and implemented in software tool (20-sim). Initially, through BG the interrelationships between elements of the system and the subsystems are structured and represented in a functional description. Then, Mathematical and iconic models are developed for the system response through simulations. In the model of antenna system c*omplexity* is reduced with the interaction of all the functional elements, flow of energy in the elements and generating the dynamic response of the system with feedback control. From the model, C code can be generated and used for the design of the controller and also be used for customization purposes. With logical steps through *model abstraction level*, development process is simplified and structured.

With the development of mechatronic module at multiple levels by illustrating all the functional components, actually reduce the complexity at domain specific design.

In order to implement mass customization in mechatronic products, two aspects are vital. *First*, the potential benefits of mechatronics come from the innovative capabilities of the technologies that facilitate to implement MC in products. Functionality in mechatronic products is enhanced, as mechanical functions are replaced by more electronics and software functions, examples are CD players, digital cameras, CNC machines, robots etc. *Second*, the design process must be based on the development of modules. Modules at defined functionality and standardized dimensions are combined to obtain functional variety. Mechatronic module composed of several disciplines of mechatronics and can be decomposed only into domain specific components. An example of mechatronic module development is illustrated in figure 11, where the respective domains are developed of defined functionality and standardized dimensions in various sizes. With these two aspects and logical steps adapted in *model abstraction level in* figure 7, companies must be able to develop customized products much faster with improved performance.

7. CONCLUSION

Design Models and methods are developed and used to get the required structuring and evaluation of mechatronic product development process. In these models, the design process steps at different levels of development are elaborated and mentioned. The significance of CAD and software tools at the system design level is shown with help of models. By using BG method in a model (integrating the multidisciplinary domains, their interaction mainly through information and energy flow and verification through simulation) basically results the reduction in complexity and development time. With logical steps through *model abstraction level*, development process is simplified and structured.

Furthermore, the role of mass customization approaches such as modular design with the structure of mechatronic systems at three levels is addressed. A mechatronic module is illustrated with all functional components and developed at multiple levels, to reduce the complexity in the process.

8. FUTURE WORK

Further issues at the conceptual design related to complexity in mechatronic system design such as *exchange of design models and data, cooperation and communication among the design engineers and support of the design of control software is not discussed in this paper*. Future work will be related to *system architecting* at conceptual design of mechatronic products and its use for mass customization.

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