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The W-Model – Using Systems Engineering for Adaptronics

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Abstract

Active systems are characterized by a steadily increasing degree of structural integration of electronic components into mechanical structures. To enable a systematic development process supporting continuous improvement the so-called W-model as a new process model for the development of active system is proposed. The W-model takes into account the mutual cross-domain dependencies in adaptronic development.
Following the principles of systems engineering, a system model based on the requirements is defined in the early phases of product development. The system model contains requirements, functions, components and the corresponding properties and parameters as well as their interdependencies. The resulting dependency-network is used during the discipline-specific detailed development for a control of the development process. Therefore integrated system simulations can be derived from the system model in which discipline-specific solutions are integrated and evaluated. Through interdisciplinary virtual validation and verification of partial and cross-disciplinary results during the development process, errors and inconsistencies are identified and can be corrected directly.
Due to the continuous use of the system model in all development phases knowledge about dependencies between system elements, can be transferred into all disciplines.

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1. Introduction

The development of technical systems is characterized by an increasing percentage of electronic components, used to influence the behavior of the mechanical structures. Also an increasing structural integration of the electronic components can be observed. Thereby the full structural integration defines the evolution of mechatronics towards adaptronics. In active systems in general, the arising mutual dependencies between the components of different physical disciplines must be considered in all phases of product development. Existing process models that describe the development of mechatronic systems lead to increasing problems in the development of highly integrated products. Therefore the Department of Computer Integrated Design has developed the W-model a new process model for the development of adaptronic systems within the LOEWE-Center AdRIA. In the W-Model

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existing process and product models are combined, further developed and enhanced using systems engineering methods. The W-model describes the development process of adaptronic systems based on a continuous integrated development using a specific development environment. In this study the W-model is described in more detail, and a concept for an appropriate development environment is presented. The contents described are discussed on a representative sample for the purpose of better understanding.

2. Adaptronics

Technical systems referred to as "active" are characterized by the use of electronic components in order to influence the mechanical behavior. The behavior adaptation can take place due to an external control was well as self-controlled due to internal or external factors. Active systems can thereby be divided into mechatronics and adaptronics.

Mechatronic systems are characterized by the use of specialized disciplines such as actuators, sensors and control technology to influence the mechanical behavior, in addition to the potential use of multiple principles for the mechanical function fulfillment [1].

Adaptronic systems in the context of this study are defined as a logical further development of mechatronics towards full structural integration. Here, the electronic components are embedded directly in the mechanical load path overtaking structural mechanical function in addition to influencing the mechanical behavior. For this, actuators and sensors used in adaptronic systems are often made of adaptive materials, which are defined by adaptive material characteristics (e.g. piezo electric materials) [2] and [3].

The difference between mechatronics and adaptronic systems is shown in Figure 1 using an Euler column. It can be seen here that in a mechatronic configuration (Figure 1, left) the electronic components are used to influence an existing mechanical structure. In adaptronic configuration (Figure 1, right) these components are integrated into the mechanical load path.

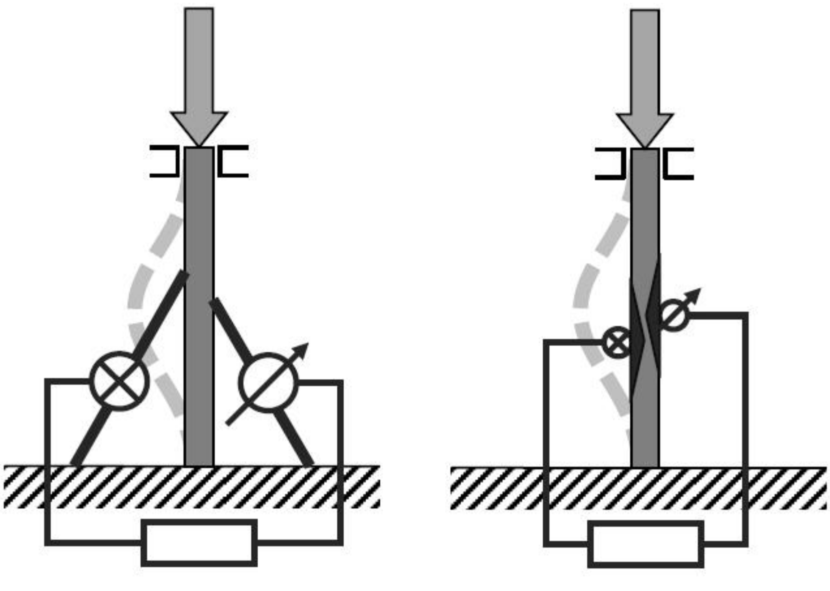

Fig. 1. Euler column in mechatronic (left) and adaptronic (right) configuration (cf. [4])

The industrial use of adaptronic systems requires fundamental advances in all disciplines involved, such as sensors, actuators, control systems as well as materials science and mechanical design methodology. For this reason, the German federal state of Hessen has founded the AdRIA-Research Center in 2008 (AdRIA - Adaptronic, Research, Innovation, Application) as part of the LOEWE-initiative (LOEWE – federal initiative for the regarding of scientific excellence). The AdRIA center was founded as a cooperation between the Technical University of Darmstadt, the Fraunhofer institution LBF and the University of Applied Sciences Darmstadt [3] and [5].

3. State of the Art

Currently, the development of mechatronic systems is often based on the V-model for the development of mechatronic systems according to VDI-guideline 2206 [6], which was derived from the original V-model for software development. The V-model, shown in Figure 2, describes the development of mechatronic systems, starting from a specific development order and divided into steps “system design”, “domain-specific design” and ”system integration”. The aim of the system design is the definition of a common solution concept that describes the product under development. Based on this concept the product and the development tasks are divided into the related domains (mechanical, electrical, information technology). Following this, the separate and parallel domain-specific development takes place. The developed solutions in the domains are then integrated into a complete system and analyzed in terms of their interaction and the requirement fulfillment. The V-model thereby describes an iterative sequence of the described steps, increasing the solution and product maturity in each iteration step. In addition to the described steps, the V-model is divided into different hierarchic level. In the highest level the product is described as a system, on the second level the system is divided into subsystems and the third level described the detailed decomposition into domain-specific solutions and components.

Studies have shown that the development process described by the V-model lead to problems by the application on the development of highly integrated systems [7].The reason for this is often a deviation from the common solution concept within the domain specific detail development. Due to a lack of communication between the involved domains and development teams, these deviations are often not communicated or analyzed for cross-domain effects. Due to that the cross-domain consequences are detected during the next system integration phase and must then be considered in additional iterations by subsequent changes.

To tackle these problems, two different approaches are applied. The first approach involves the earliest possible consideration of cross-domain dependencies. Therefore often the methods of systems engineering are applied. Systems engineering is based on the concepts of systems theory. A complex system is decomposed into its individual components. The components are considered individually and in relation to each other [8]. In addition, a variety of methods are used, in particular for controlling system and model complexity. As an example the use of dependency structure matrices should be mentioned. Design structure matrixes allow the systematic structuration of system elements and their dependencies [9]. In particular, indirect dependencies can be analyzed.

The second approach is based on the improvement of the cross-domain communication in the stage of domain-specific design. In addition to a variety of solutions that offer an integration of specialized domain-specific tools also approaches exist to coordinate the development process through the use of a common database. As an example Bellalouna proposes a cross-disciplinary integration platform [10]. Bellalouna uses a product data management system as a central database in the mechatronic design process described in the V-model. The domain specific authoring tools and data management solutions are connected to the integration platform by service oriented architecture adapters. In general studies have shown that the use of integrated software tools and integrated development environments lead to shorter development times through a cross-domain integration in the early phases of product development [11].

A different view on the product development is described by the “Münchner Vorgehensmodell” (Munich Proceeding Model) (MVM) [12], shown in Figure 3. In the MVM the development of products is seen as a process of problem solving. Therefore the MVM contains seven elements of problem solving: “target planning”, “target analyzing”, "structuring of problems”, “identification of solutions”, “determination of properties”, “decision” and “verification of achievements”. Unlike linear models with the possibility of recesses or iterations, the MVM is visualized as a network structure. The MVM is thus closer to real development processes, which are characterized by frequent changes and iterations, than linear process models. The MVM also includes the fact that the individual elements of problem solving are not always clearly distinguishable in practical applications. Therefore the individual elements are overlapping in the MVM.

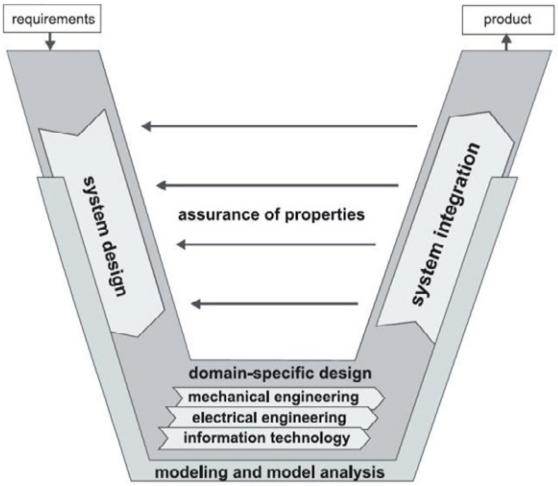

Fig. 2. V-model for the development of mechatronic systems [6]

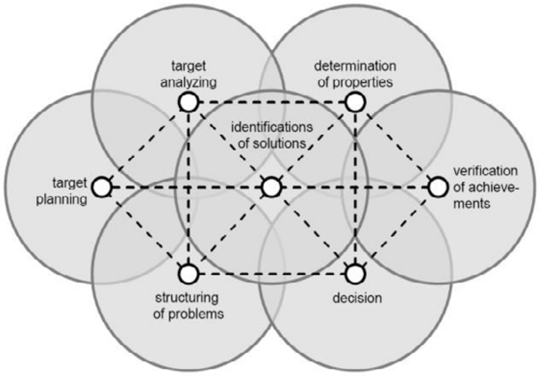

Fig. 3. Munich proceeding model (MVM) (cf. [12])

Most proceeding models describe a development process in which the system to be developed goes through various stages of product maturity. The properties of the product are described by a variety of models, which becomes more concrete through the development process. An example is the "Modellraum des Konstruierens" (Model Space of Construction) by Rude [13]. Following Rude, product development das the levels of requirements, functions, principles and shape. In each level the product features are described by appropriate models with the possibility of model variation, limitation, decomposition and assembly. Final step of construction is the integration of models to a final solution on the shape level.

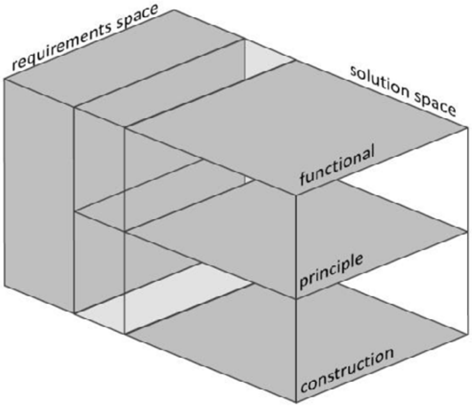

Fig. 4. Munich product specification model (MKM) (cf. [14])

Based on the model space of construction the "Münchner Produktkonkretisierungsmodell" (Munich Product Specification Model) (MKM) was developed [14]. The MKM consists of the two major components "solution space" and "requirements space", where the "solution space" is divided into the three levels of "functional", "principle" and "construction." In contrast to the model description by [13] the MKM emphasizes the special role of requirements. Within the MKM the requirements are not on an abstract level above the functions but will be enlarged, detailed and further developed during the product development process. In addition, the MKM demands a constant verification of the models on different levels of detail in terms of the corresponding requirements [14].

4. W-Model for the development of adaptronic systems

Due to the high degree of integration of adaptronic systems and the problems outlined in the application of existing process models for mechatronic product development, a new proceeding model was developed by the Department of Computer Integrated Design [15]. The new W-model for the development of adaptronic systems is based on the V-model according to VDI Guideline 2206 [6].

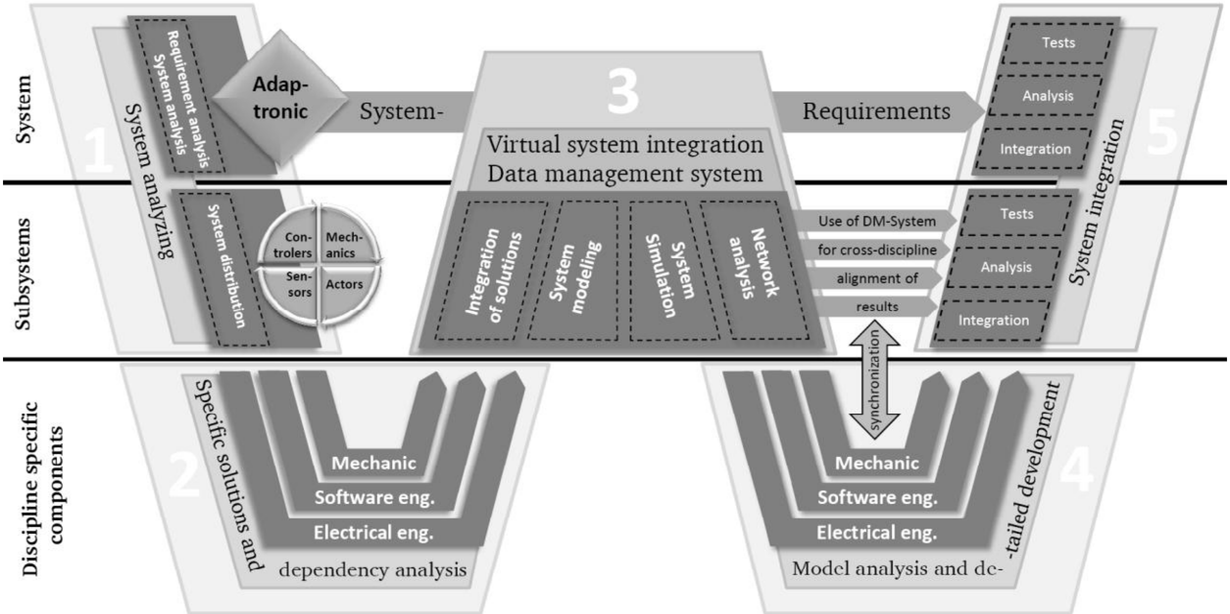

Fig. 5. W-model for the development of adaptronic systems [16]

The W-model for the development of active systems is derived from the existing W-model for software development. The W-model of software development provides an analysis and verification of development results, parallel to the phases of the system definition and integration [17], [18]. Following the original W-model, the W-model for the development of active systems describes a development process which is characterized by a permanent virtual validation. In contrast to W-model for software development the integration is performed cross-domain, based on a common system models and simulations.

The W-model for the development of adaptronic systems assumes the hierarchical structure of the V-model with the levels "System", "Subsystem" and "Discipline specific components". In contrast to the V-model, the W-model describes the development using five steps: “System analyzing“, “Specific solutions and dependency analysis“, “Virtual system integration“, “Model analysis and detailed development“ and “System integration“. Central element is the new step “Virtual system integration” defining the name giving “W”-shape.

This step involves the integration and networking of the requirements, functions and systems architecture with the domain-specific, detailed development work. This allows analyzing domain-specific work in a system context without performing manual system integration. In addition, the W-model can also support a non-linear process of development with leaps and iterations between the phases of requirements and feature definition and solution finding. Adaptions to the requirements or functional structures can be directly transferred into the domain-specific detailed design process and require no additional integration and analysis iterations. Through that, the W-model for the development of active systems is able to better support actual development processes than the V-model.

4.1. System analyzing

The first step of the W-model is largely analogous to the step "system design" of the V-model. In this first step the product to be developed is analyzed. For this purpose, the requirements, which are documented within the specifications, are recorded and analyzed. The atomic requirements are structured and an initial decomposition into partial requirements is done. From the resulting requirement structure then a first functional structure is generated. As a preparation for the next development step the requirements and functions are then distributed into the individual domains. Based on the shown hierarchy levels this first step is located on the levels "System" and "Subsystems".

4.2. Specific solutions and dependency analysis

The second step of the W-model treats the domain-specific definition and delimitation of the solution space. For this purpose, in each domain the known product design methods for solutions finding are used (e.g. morphological boxes). Analog to the V-model the work is done parallel and independently. The work of the various domains is related to the functions and requirements defined in the first step.

In addition to defining the solution space an analysis of the identified solutions in terms of their respective properties and critical system parameters, as well as the internal and external dependencies, is performed. The emerging domain specific parameter-property-network is used in the following step for the creation of a multidisciplinary dependency-network.

The distribution of the structures, defined in the first two steps, into requirements, functions, principles and solutions is largely analogous to the four levels of the model space of constructing according to Rude [13].

4.3. Virtual system integration

In the third step the W-model describes the virtual integration of the domain-specific solution space defined in step two to a product solution space. The solution space describes the common set of all possible combinations of domain-specific component solutions taking into account the global requirement fulfillment. The global product solution space is then analyzed and potential alternative solutions are derived. For later variant analysis and selection also criteria are defined and weighted, based on the documented requirements.

For each variant generic system models can be created, linking the existing requirement and functional structures from the first step with the variant-specific system structures. By connecting the system structures the existing requirements and functional structures will be extended. In particular, the additional internal requirements and functions devoted from the individual elements of the system structures must be considered. In this way, the variant-spanning system models are detailed to variant-specific models. By adapting and extending the requirements and functions because of the structures derived from them, the modeling results in a holistic, bidirectional system model.

The variant-specific system models will be extended with the respective properties and parameters. For this, the domain-specific parameter-property-networks, which were created in the previous step, are used. For the analysis of system models with respect to the dependencies of the contained elements, the methods known from literature (e.g. design structure matrices) are applied.

For the virtual validation of development results simulations of system behavior are defined. For this purpose, critical system properties for requirement fulfillment are identified. Then integrated simulations are created, determining the properties by key parameters of the parameter- property-network. By defining the simulations in the level of subsystems and systems instead of the level of domain-specific-components the virtual verification of system properties is not linked to individual, domain-specific developments or tools. Through this it becomes possible to give statements about the maturity and requirement fulfillment of the system without leaving the integrative, cross-domain level.

Important feature of the W-model is that the created structures for the requirements, functions and system components, as well as their bidirectional dependencies, are not a closed, fixed result, as described in the model space of construction by Rude [13]. Following the W-model, the various structures provide a starting point for the detailed domain-specific development. During the detailed design process, the individual structures, as well as the holistic system model, are continually adapted, expanded and detailed due to the domain-specific results. The process described by the W-model can thereby be compared with the Munich product specification model [14], which proposes an extension and detailing of the requirement structure as part of the development process. Unlike [14], the structural adjustments proposed in the W-model are not limit only to the requirements but involving all structures involved in the development process.

4.4. Model analysis and detailed development.

In the fourth step, the W-model describes the detailed development of solution. Starting point is the system model created in the third step.

Analogous to the V-model the development of partial solutions is done parallel within each domain. Due to the permanent linking of the domain-specific data-sets to the system model the developments are not independent from each other. The linking is done by the use of the inner parametric structures of the domain specific authoring systems.

Due to the permanent linking the W-Model provides a continuous synchronization between the domain-crossing system level and the domain-specific detailed development. Development steps and changes that cannot be expressed by changes of parameters or properties require an adaption of the system model. Because of the permanent coupling of the system model with the domain-specific solutions and models, adjustments of parameters as well as adaptions to the system model, e.g. additional requirements or adaptions to the system architecture, can be communicated across domains at any time.

In addition, system simulations defined in step three are used to analyze the system characteristics and requirements fulfillment.

4.5. System integration

As a final step in the development of active systems the W-model describes the integration of the final domain-specific solutions to subsystems and systems as well as physical validation using prototypes. Unlike the V-model this step is not absolutely necessary to give a statement about the general functioning of the system, due to the permanent virtual verification within the detailed development.

5. Application scenario for the development of adaptronic systems

In the following the application of the processes proposed by the W-model are demonstrated on a representative, adaptronic example. Therefore an adaptronic engine bearing, which was developed in the LOEWE-Center AdRIA [19] is used. First the active engine bearing is described briefly. Then the definition of the corresponding system model and system simulation as well as their use in the detailed development is explained.

Core function of the engine bearing is the elimination of vibration transmissions between the engine and connection structure (e.g. housing) in a maritime usage. This is to avoid unwanted sound radiation by vibrating housing surfaces. This is currently done by constructive reinforcements of the surfaces. Therefore the engine bearing will be located at the interface of engine and housing, compensating the engine vibrations by inducing counter-vibrations. For the analysis of the engine vibrations and for the induction of counter-vibrations piezoelectric elements are integrated in the components of the engine bearing [19].

According to the W-model the functional and non-functional requirements are captured in detail. In addition to requirements for the passive behavior of the engine bearing (the maximum and minimum dimensions because of the available space, minimum load, connectors and interfaces), there are also requirements regarding the active behavior (amplitude and frequency ranges, lifespan, maximum power consumption). From the requirements, a first functional structure is derived. The functions for the active behavior include for example "oscillation amplitude measure", "detecting vibration frequency", "counter-vibration calculation" and "induce counter vibration".

Fig. 6. Prototype of an active engine bearing [20]

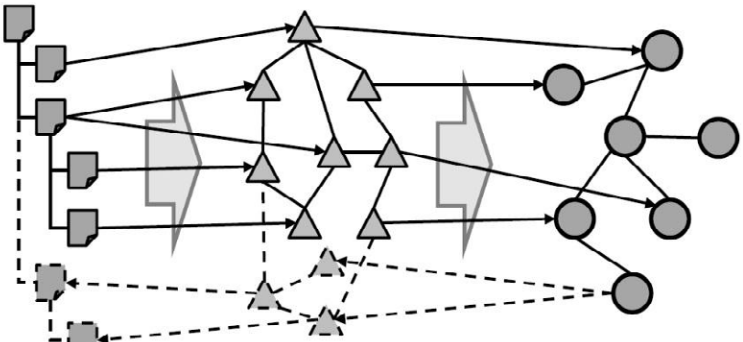

Fig. 7. Bidirectional transfer of requirements-, functions- and system-structure

In the next step for each function the respective solution space is spanned by the corresponding domains. The solution spaces are integrated and an initial system structure is created. In the system structure, the system element "piezo actor" is added and linked with the function "induce counter vibration". Because of the individual system elements internal requirements and functions can be generated, which must be added in the requirement and function structure. In this example, the system element "piezo actor" lead to the function "voltage transformation", but also to the additional requirements "maximum temperature in the engine bearing" and "maximum humidity in the engine bearing", linked to the requirements regarding the life time. This also lead to additional requirements treading the geometric structure and the used piezoelectric materials.

The derivation of the system structures from functional structures and the adaptation of the requirements and functions because of the system elements are shown in Figure 7.

After the creation of the system model the integrated simulation is defined. For this, the concept for modular simulations of active systems proposed by Herold et al. is used [21]. The used simulation modules are determined by the elements of the system structure and the properties required for requirement fulfillment.

The modular simulation of the engine mount is realized using Matlab Simulink [21]. The input and output desks of the simulations are linked with parameter-property-network of the system model. As a result, the simulations are able to calculate the global, requirement-critical system behavior because of the key parameters at any time of the subsequent development process.

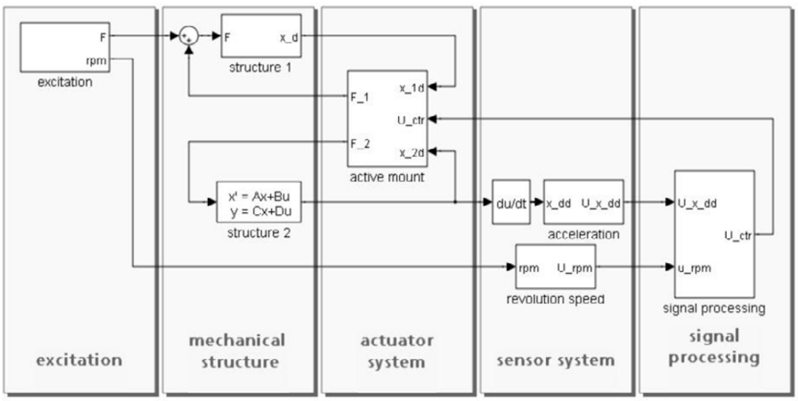

Fig. 8. Simulation of active engine bearings global behavior [21]

In detailed development domain-specific authoring tools (such as CAD) are coupled to the system model and the parameter-properties-network by appropriate parametric systems. This allows transferring adaptions to specific data-sets of individual domains by adjustments of parameter values within the network. In the shown example the generated simulation is used to analyze changes in terms of the system's behavior, cross-domain dependencies and requirements. The changes are evaluated and necessary adaptions in other domains are detected.

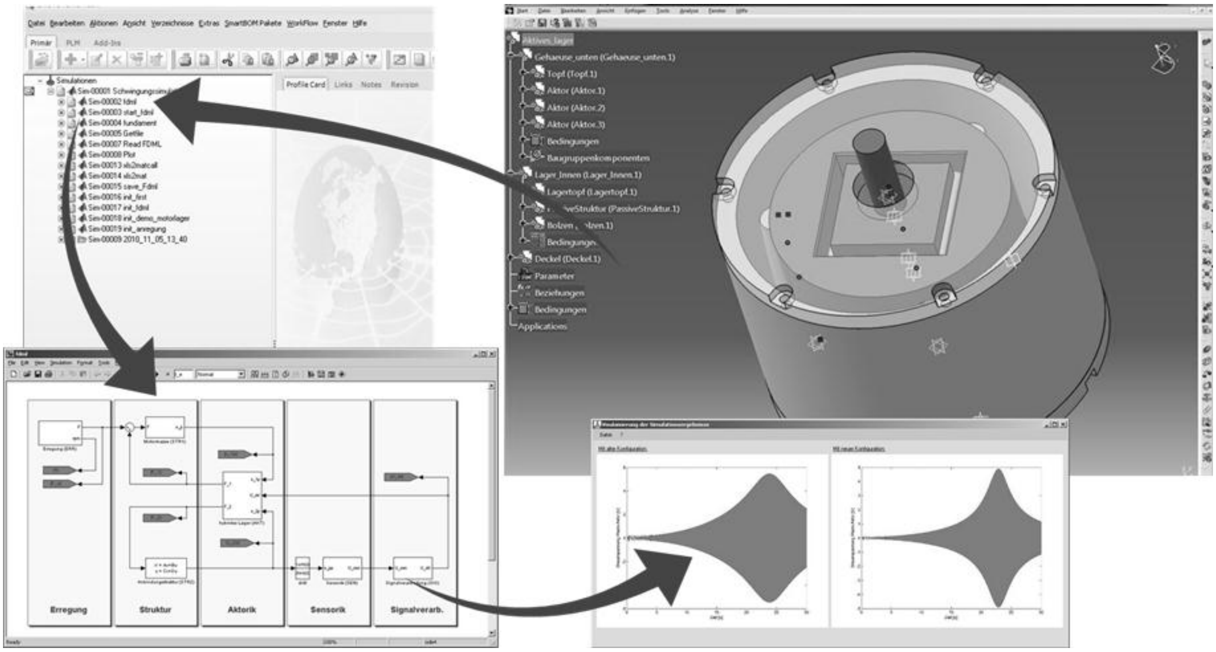

Fig. 9. Using the integrated system simulation in adaptronic system development

Figure 9 shows how adjustments to the geometry in the domain of mechanical design are analyzed across domains. The analyzed properties are the systems vibration behavior and the behavior of the piezoelectric actuator. In the described engine bearing the piezo actuators are directly integrated into the mechanical structure. Thereby geometry changes have a major impact on the work area of the actuator.

Within the mechanical design the height of the bearing is changed in the development process. For this, a CAD-system is used, in which the geometry of the corresponding components is adjusted. The changes to the model-parameters are analyzed and transferred into the central parameter-property-network. The changes to the system properties are automatically calculated using the defined system simulations and compared with the documented requirements.

In the used example, the analysis shows that the adjustments to the geometry would result in a required actuator voltage, which is not compatible with the properties of the actuator material. Therefore, the changes to the geometry without an adjustment in other domains (e.g. change of actuator material) are not allowed.

6. Conclusion

Adaptronic systems are characterized by the structural integration of electronic components in the mechanic load path. The inter-dependencies between the components of different domains, resulting from the high level of integration, have to be considered in all phases of product development. Existing approaches and process models for the development of mechatronic systems lead to problems with increasing degree of integration. They are therefore not applicable to the development of adaptronic systems. In this paper, a new process model, developed by the Department of Computer Integrated Design, is presented. The new W-model for the development of adaptronic systems is based on the V-model of the mechatronic product development. Central core of the W-model is a continuous, virtual, cross-domain integration and verification. This is intended to avoid divergent development at an early stage in the development process and to minimize time-consuming iteration processes. The W-model is divided into the five steps "System analyzing", "Specific solutions and dependency analysis", "Virtual system Integration", "Model analysis and detailed development" and "System integration". In the present study, the individual steps of the W-model are explained in detail, and the application development process proposed in the W-model is explained, using an adaptronic engine bearing developed in the LOEWE-Center AdRIA.

References

1. Isermann, R.: Mechatronic systems: Fundamentals. Springer, London [u.a.] (2005)
2. Hanselka, H., Bein, T., Breitbach, E., Krajenski, V.: Mechatronik/Adaptronik. In: Hering, E., Bein, T. (eds.) Grundwissen des Ingenieurs. Mit 265 Tabellen, 13th edn. Fachbuchverl. Leipzig im Carl Hanser Verl, München [u.a.] (2002)
3. Bein, T., Hanselka, H.: Das LOEWE-Zentrum AdRIA: Adaptronik - Research, Innovation, Application. 3. Konferenz des DVM - Arbeitskreises "Zuverlässigkeit mechatronischer und adaptronischer Systeme", Darmstadt (2010)
4. Malzacher, J.: Leistungssystem zur integrativen virtuellen Produktentwicklung adaptronischer Systeme. Shaker, Aachen (2010)
5. Bös, J., Hanselka, H.: LOEWE-Zentrum AdRIA - a multidisciplinary research project on the advancement of active systems. In: Proceedings of the 16th International Congress on Sound and Vibration, Kraków (2009)
6. Verein deutscher Ingenieure: Entwicklungsmethodik für mechatronische Systeme. Beuth Verlag, Berlin(2206) (2004)
7. ProSTEP iViP Documentation: Mechanic Process Integration (MPI), Darmstadt (2009)
8. Daenzer, W.F., Haberfellner, R.: Systems engineering: Methodik und Praxis, 11th edn. Verl. Industrielle Organisation, Zürich (2002)
9. Lindemann, U., Maurer, M., Braun, T.: Structural complexity management: An approach for the field of product design. Springer, Berlin (2009)
10. Bellalouna, F.: Integrationsplattform für eine interdisziplinäre Entwicklung mechatronischer Produkte. Shaker, Aachen (2009)
11. Jackson, C.K.: The Mechatronics Systems Design Benchmark Report: Coordinating Engineering Disciplines. Aberdeen Group (2006). Accessed 25 May 2011
12. Lindemann, U.: Methodische Entwicklung technischer Produkte: Methoden flexibel und situationsgerecht anwenden, 3rd edn. Springer; Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg (2009)
13. Rude, S.: Wissensbasiertes Konstruieren. Shaker, Aachen (1998)
14. Ponn, J., Lindemann, U.: Konzeptentwicklung und Gestaltung technischer Produkte. Springer Berlin Heidelberg, Berlin, Heidelberg (2011)
15. Nattermann, R., Anderl, R.: Simulation Data Management Approach for Developing Adaptronic Systems - The W-Model Methodology. In: Proceedings of the WASET 2011 International Confernce on Software and Data Engineering (ICSDE), pp. 429–435, Bangkok (2011)
16. Anderl, R., Nattermann, R.: Integration of Systems Engineering and Parametric Modeling for Adaptronic Systems. In: ProSTEP iViP e.V. (ed.) ProSTEP iViP Symposium 2012, Hamburg (2012)
17. Jin-hua, L., Qiong, L., Jing, L.: The W-Model for Testing Software Product Lines. In: Yu, F. (ed.) Proceedings, International Symposium on Computer Science and Computational Technology. ISCSCT 2008; Shanghai, China, 20-22 December 2008, pp. 690–693. IEEE Computer Society, Los Alamitos, Calif. (2008)
18. Spillner, A.: W-Modell. In: Spillner, A., Linz, T., Roßner, T., Winter, M. (eds.) Praxiswissen Softwaretest - Testmanagement. Aus- und Weiterbildung zum Certified Tester - Advanced Level nach ISTQB-Standard, 2nd edn. Dpunkt, Heidelberg, Neckar (2008)
19. Kauba, M., Herold, S., Koch, T., Mayer, D., Melz, T.: Design and application of an active vibration control system for a marine engine mount. In: International Conference on Noise and Vibration Engineering, Leuven, pp. 241–255 (2008)
20. AdRIA: Adaptronik - Research, Innovation, Application. Die Kunst der Anpassung, Darmstadt, www.loewe-adria.de (2011)
21. Herold, S., Jungblut, T., Kurch, M.: A Systematic Approach To Simulate Active Mechanical Structures. In: Multi-Disciplinary Simulations - The Future of Virtual Product Development, Wiesbaden (2009)