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SIMULATION-BASED CONCEPT GENERATION FOR MECHATRONIC SYSTEMS

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1. Introduction

Mechatronic design methodology has become a very important field during the last decade. Since the inherent complexity of mechatronic systems influences both the product and its development process, new methodologies and methods are required to cope with the associated challenges. The use of simulation is one very promising possibility for improvement [Rajarishi et al. 2011] leading to the aim of simulation-based design where simulation is the primary means for design evaluation [Shephard et al. 2004]. Nevertheless, studies by the authors Dohr and Vielhaber [2012b, 2013] have shown that despite the fact that there are very sophisticated simulation techniques [2012a], no design methodology integrates simulation in the above mentioned way. At the moment simulation is rather used as a tool that supports or substitutes physical prototypes at the traditional stages. This is the reason why the authors developed a framework for simulation-based mechatronic design which is based on a process model that focusses on the specific needs of simulation-based design.
In this paper, the developed approach is validated for the early phases, which means for conceptual system design. For this purpose a mechatronic system is chosen on which the development with the simulation-based design framework is exemplified. Especially those early phases benefit from the use of modeling and simulation techniques because they provide an integrative platform for finding the best solution concepts within the large solution space of mechatronic systems [Commerell et al. 2008].
In the next section the developed framework is briefly described. In section 3 the choice of a suitable mechatronic system and the system itself are described. The validation of the approach is conducted on the development of an active suspension for bicycles. The detailed procedure for early conceptual design is described in section 4. Based on the results the applicability of the developed methodology and open issues are discussed. Finally an outlook on further activities is given.

2. Simulation-based design framework

In [Dohr and Vielhaber 2013] the authors presented a process model which builds the basis for a simulation-based design framework. A simplified generic version is shown in Figure 1. The inputs for the process are the requirements that are put on the product. The process steps are oriented on the steps of the V-model from VDI 2206 [VDI 2004] and hence the process itself is divided into three main phases – conceptual system design, domain-specific embodiment design and system-level integration. Those phases only build a generic basis and can be adapted and supplemented to any company specific process. The process model is further divided into two parallel streams – design activities and analysis activities – which are closely interlinked. The control variable “s” in Figure 1 is used to express different levels of system hierarchy. This means that the conceptual system design phase is executed several times on increasingly deeper level of hierarchy, until development tasks can be assigned to

single domains or departments. The analysis activities stream is intended to enable consistent analysis through simulation along the entire process instead of analysis that is limited to single – mostly late – stages. The management of simulation or generally analysis activities is done through Analysis Milestones (AMS). They contain information about when and how an analysis has to be done. The contents of Analysis Milestones are shown in Figure 2, a more detailed description is provided in [Dohr and Vielhaber 2013, 2014]. Based on the criteria defined in those milestones they also serve as a link back to design activities if an analysis does not fulfill those criteria. In this way a consistent synthesis-analysis-cycle is enabled as exemplarily illustrated in Figure 1 in the first phase. The benefit of simulation is that those cycles can be kept very small since designs can be analyzed more or less in parallel to their generation. As a result of this, several micro-iterations replace the macro-iterations covering multiple phases. Nevertheless, if it should be necessary, macro-iterations are also possible. Such synthesis-analysis-cycles are generally run through several times during a single phase resulting in an increasingly detailed design and increasing knowledge and hence there are also several Analysis Milestones, indicated by the subscriptions "1..m/n/o". A rough structure of the Analysis Milestones should be defined prior to design activities based on the requirements definition. This procedure has been adopted from software and electronic design where test planning is already conducted very early in the process [Dohr and Vielhaber 2012b]. In the course of the development process, level of detail and maturity of design are growing and thus knowledge about the system is growing [Ullman 2010]. So those preliminary milestones have to be adapted during the design process and also new ones may be added. In order to profit from the ability of simulation as a means for the comparison of different design alternatives [Wall 2007] and in order to manage parallel design and analysis activities, Analysis Milestones can also be processed in parallel. Only if the criteria of the corresponding milestones are fulfilled, the next design phase can be started.
The output of the process is either a prototype of high maturity or – for an ideal simulation-based design process – the final product.
For further information about the process model and the overall framework including methods see [Dohr and Vielhaber 2012b, 2013, 2014].

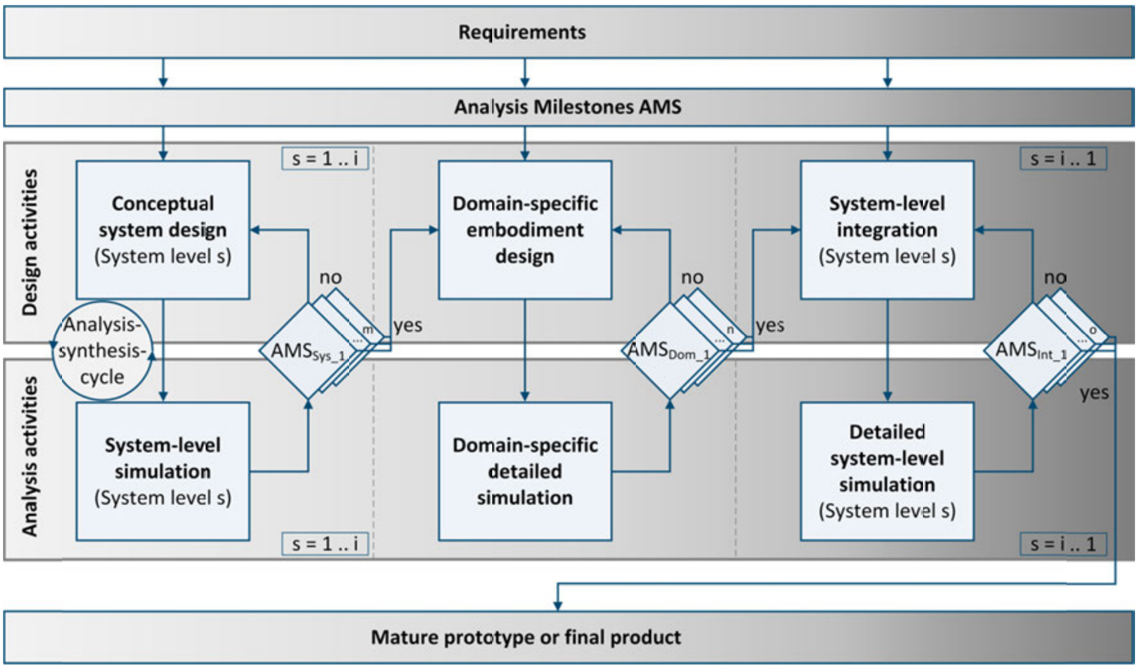

Figure 1. Abstract overview of the simulation-based mechatronic design process model

For easier and consistent description of the processes and methods related to the simulation-based framework, the authors use a description based on the CPM-terminology of Weber et al. [2003]. As depicted in Figure 3, this means that in the design activities stream the characteristics C_i of the system are defined in order to fulfill the required properties PR_j. In the analysis activities stream the actual properties P_j are determined and compared to the required properties PR_j. Based on this comparison decisions on further steps can be derived. A detailed description of the CPM-based description of the framework is provided in [Dohr and Vielhaber 2014].

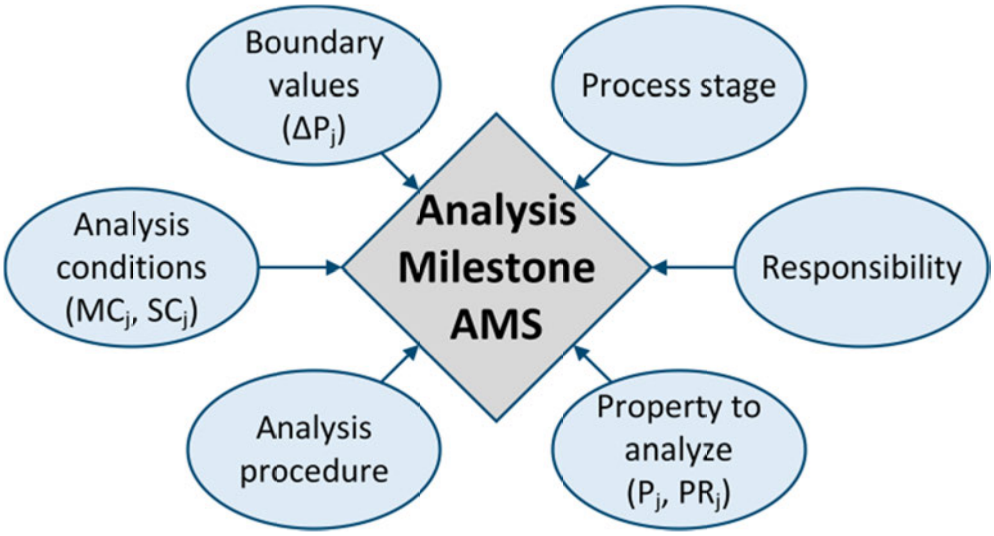

Figure 2. Analysis Milestones and the contained information

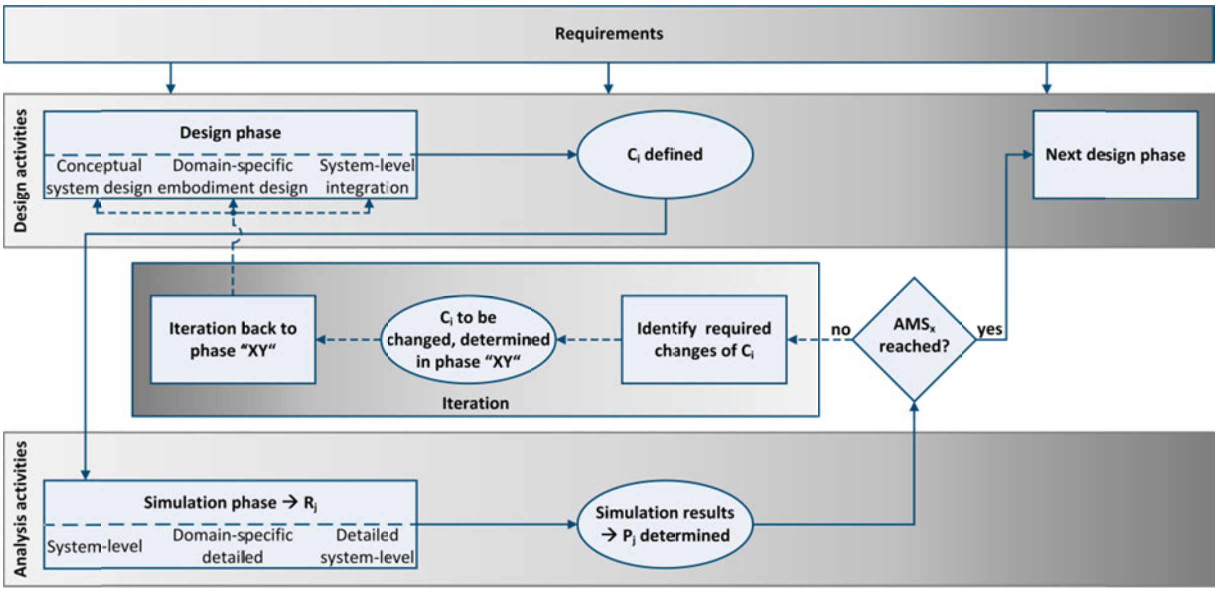

Figure 3. Analysis-synthesis-cycle between design activities and analysis activities streams

3. Choice and description of the validation product

In order to validate the framework described in the previous section, an example of a mechatronic system is used on which the framework can be applied. For this purpose an active suspension for bicycles has been chosen for validation purposes which represents a typical mechatronic system but is not too complex in order to be still manageable. As a platform for the implementation the bicycle depicted in Figure 4 is used which comes standard with a regular, passive shock absorber for the rear suspension. Such a passive shock absorber is used to damp the vibrations and shocks that are induced be unevenness of the riding surface. Nevertheless, the vertical movement of the wheel is transferred to the seat/saddle resulting in a reduced riding comfort. Moreover such a passive damper in general cannot be easily adjusted to different surfaces, e.g. even road or off-road terrain. In order to improve riding comfort and stability this passive system is to be replaced by an active mechatronic systems. It

is intended to minimize vertical movement of the saddle or the seat by compensating vibrations and unevenness of the surface.
In the next section, the framework described in section 2 is applied on the development of the active suspension. The focus is set on early conceptual design stages which include concept generation and validation.

Figure 4. Bicycle used for validation purposes [HP Velotechnik 2013]

4. Conceptual system design for an active suspension

The conceptual system design phases contain the following activities in the design activities stream [Pahl et al. 2007], [Dohr and Vielhaber 2013]:

- Definition of product functionality
- Partition into subfunctions
- Definition of interfaces
- Generation of solution concepts
- Assignment of functions and modules to domains or departments

In parallel to this, the analysis activities stream concentrates on system-level simulation of the system to analyze its basic behavior. In the conceptual system design phase those simulations have several purposes:

- Offering a sound means for comparison of different design concepts
- Derivation and refinement of requirements based on simulation results
- Offering information for the improvement of one or more concepts

Design in the conceptual system design phase is done on system level involving experts of all domains who interact in order to find the best solution concept [Möhringer 2004]. Hence simulation has also to be done on system level with a lower level of detail instead of using very detailed, domain-specific simulations [Paredis et al. 2001]. There are several domain-independent simulation tools available [Dohr and Vielhaber 2012a]. Among those, Modelica-based tools [Modelica Association 2013] have several benefits for the purpose of conceptual design of mechatronic systems and hence are well-suited:

- The easy-to-handle graphical representation is comprehensible to all domains because domain-specific aspects are represented in domain-specific notation
- The mathematical description is generated by the software in the background but can also be extended or modified, should this be necessary

- The use of component libraries assists the generation of concepts based on functions
- Systems can directly be simulated in one tool and thereby concepts are easy to compare

Moreover most of the tools offer the possibility to create simplified models of multibody systems which often build the basis of mechatronic systems [Schiehlen 1997], [Wallaschek 1995]. Those are the reasons why in the context of this paper the Modelica-based tool SimulationX [ITI GmbH 2013] has been chosen for simulation purposes.

4.1 Requirements and initial Analysis Milestones

The starting point for the process as depicted in Figure 1 is a set of requirements that are put on the system that is to be developed. In the case of this validation example, those requirements have been very rough which means that only the basic geometry details and some basic restrictions for functionality of the system – like its reaction time – have been known. Further requirements will arise or will be derived in the course of the development. Based on these requirements a first set of Analysis Milestones has been derived for the conceptual system design phase. A selection of those milestones is depicted in Table 1.

Table 1. Preliminary set of Analysis Milestones for conceptual system design

<table>
<tr><th>Analysis Milestone</th><th>Property P_j</th><th>Value for P_j</th><th>Boundary value ΔP_j</th><th>Analysis procedure</th><th>Analysis conditions</th></tr>
<tr><td>AMS_{Sys_1}</td><td>Energy consumption</td><td>TBD Comparison of concepts</td><td>-</td><td rowspan="3">System-level simulation, SimulationX</td><td rowspan="3">Simplified models</td></tr>
<tr><td>AMS_{Sys_2}</td><td>Reaction time</td><td>0,5 s</td><td>max</td></tr>
<tr><td>AMS_{Sys_3}</td><td>Deviation of seat position from desired value</td><td>10 %</td><td>+/-</td></tr>
<tr><td>AMS_{Sys_4}</td><td>Overall weight of the actuation system</td><td>5 kg</td><td>max</td><td rowspan="2">Estimation</td><td rowspan="2">Based on experience and rough analyses</td></tr>
<tr><td>AMS_{Sys_5}</td><td>Material cost of prototype</td><td>3500 €</td><td>max</td></tr>
<tr><td colspan="6">After concept selection (AMS_{Sys_1}… AMS_{Sys_5} have been passed)</td></tr>
<tr><td>AMS_{Sys_6}</td><td>Reaction forces</td><td>Derived from simulation</td><td>-</td><td rowspan="2">System-level simulation, SimulationX</td><td rowspan="2">Simplified 2D multibody model with actuator and simplified controls</td></tr>
<tr><td>AMS_{Sys_7}</td><td>Required actuator speed</td><td>Derived from simulation</td><td>-</td></tr>
</table>

4.2 Generation and choice of solution concepts

The generation of solution concepts is done according to the procedure proposed by Pahl et al. [2007]. Hence based on the requirements the product functionality is identified and after that divided into subfunctions to manage complexity. The resulting function structure of the system is depicted in Figure 5. Through the identification of working principles to each subfunction an overall solution concept can be generated [Pahl et al. 2007]. Here design catalogues, as e.g. described by Roth [2000], can be used to identify suitable working principles. At this point one of the benefits of Modelica-based tools can be used: they contain standard libraries of models from different categories (mechanics, hydraulics, electronics, controls …). Those can also be used as design catalogues. Moreover those models are well documented which means that the structure and the behavior of the specific element or physical effect is described. One of the main assets of using model libraries as design catalogues is that the behavior is already mathematically described and the physical interfaces are already defined in the model. So the compatibility of the individual working principles can be directly checked and the system behavior can be easily modeled by connecting the individual models of each subfunction.

Furthermore it is possible to create own libraries so that company- or product-specific aspects can be integrated. This also offers the possibility of creating "early-phases" models which are less detailed and thus more applicable in the conceptual design phase. In the presented example only the standard libraries have been used.

Of course there are several iterations as depicted in Figure 1 as analysis-synthesis-cycles. Hence the milestones AMS_{Sys_1} to AMS_{Sys_6} have to be passed several times, certainly combined with a growing level of detail. However those iterations are currently not specifically marked in the milestones.

For a more detailed modeling of the structure, the functions and the internal processes of the system, SysML [Object Management Group 2013] has been used, at least where it is reasonable. For example the requirements diagram has not been used because there are other tools that are more suitable for requirements management. A more detailed description of the SysML modeling would go beyond the scope of this paper.

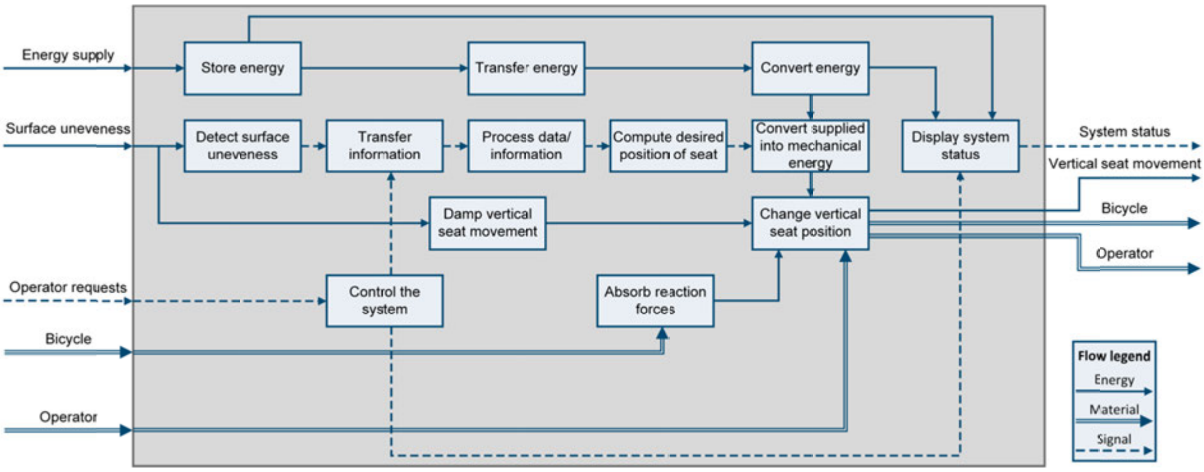

Figure 5. Function structure for an active suspension of bicycles

In the function structure the most important subfunction is "change vertical seat position" in combination with "damp vertical movement". For those two functions mainly three solution concepts have been considered (other concepts could have been excluded because they do not fulfill fundamental requirements):

- electromechanical linear actuator
- pneumatic linear actuator
- hydraulic linear actuator

All of them can be combined with a separate damper, a separate spring or a combination of both.

Since most of the other subfunctions depend on the choice of one of these three concepts, they have been compared by running system-level simulations in SimulationX – including all combinations with dampers and springs. For the simulation two simplified load cases (LC) have been derived from the requirements:

- Ride over curb (LC1): curb height 100 mm, passing time 0.5 s
- Ride on uneven surface (LC2): sine wave-form with amplitude 50 mm and frequency 0.5 Hz

At this point the level of detail in design has significantly raised so that the initial Analysis Milestones have to be adapted, which is exemplified for AMS_{Sys_2} in Table 2.

Table 2. Example of adapted Analysis Milestones based on new design information

Analysis Milestone	Property P_j	Value for P_j	Boundary value ΔP_j	Analysis procedure	Analysis conditions
AMS_{Sys_2}	Reaction time	0,3 s for LC1	max	System-level simulation, SimulationX	Only actuators with simplified control algorithms
		0,5 s for LC2	max		

In this way Analysis Milestones are permanently updated to the current development status. It is also possible to add new milestones, which is for example necessary after the final concept selection.
In Figure 6 two of the models which are used for the comparison of concepts are shown.
Based on the simulations that have been run, the electromechanical principle promises to be the best-suited concept. In addition to the simulation results, several criteria have been considered which cannot be simulated at this stage of design. For example the effort for the peripheral components of the hydraulic and pneumatic concepts might be too large to be implemented within a bicycle. Furthermore a continuous control of a pneumatic actuator is hard to realize. The benefit of using the simulation results is that the assessment of different concepts which are characterized by subjective decisions – like e.g. the approaches proposed in VDI 2223 [VDI 2004] – can be supported by profound simulation results. Based on such an assessment, in the following the electromechanical actuator is further detailed. This concept is similar to the suspension system of Bose [Bose Automotive Systems Division 2013].

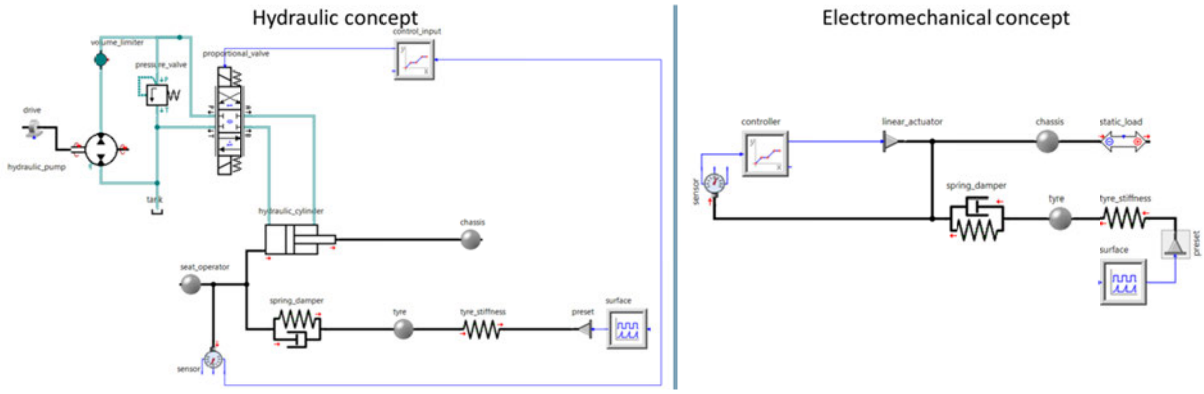

Figure 6. Simulation models of the different concepts

At this point the first iteration within the conceptual system design phase back to the design activities has to be started in order to detail the system concept with the electromechanical actuator.
In order to get more accurate results the model is combined with a simplified 2-dimensional multibody system which can also be modeled within SimulationX. The model is depicted in Figure 7. Furthermore the control algorithm has been further detailed from an ordinary PID-controller to a Skyhook-based algorithm as described in [Karnopp et al. 1974].

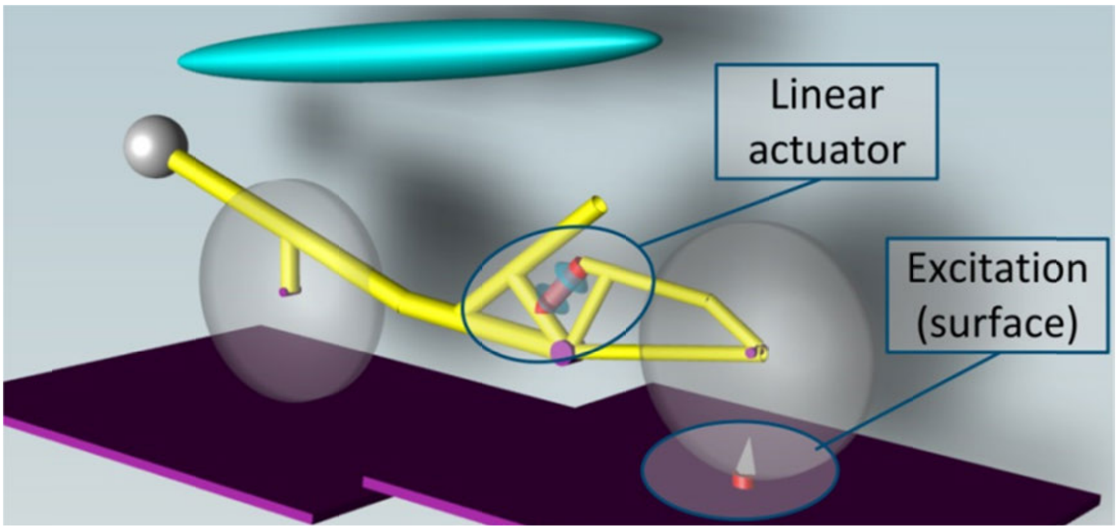

Figure 7. Simplified multibody model

In a first step this model has been used on AMS_{Sys_6} and AMS_{Sys_7}. Hence the reaction forces and the required actuator speed are determined based on the desired system behavior. The results for the forces in both load cases are depicted in Figure 8. Those are mainly independent of the actuator choice and only depend on the geometry and load cases.

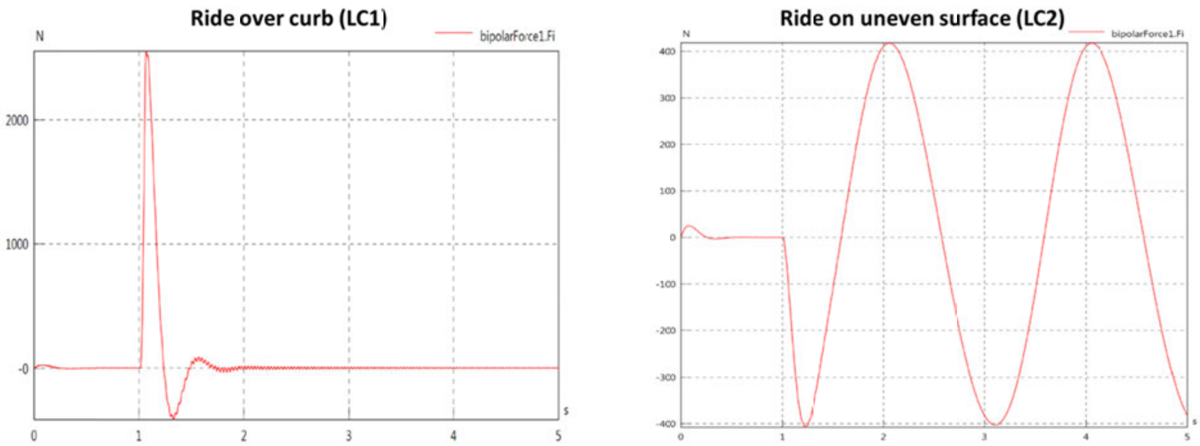

Figure 8. Reaction forces for the two load cases

Since the actuator is planned as a bought-in part, the simulation results can now be used to search for suitable products. If none can be found, the available actuator models can be used to refine the requirements on the system – e.g. control accuracy – based on simulations with the specifications of available actuators. In this specific case a rough market analysis has shown that there are suitable actuators available. At this point, all Analysis Milestones for the conceptual system design phase have been passed and the system concept is defined. Hence the conceptual system design phase is finished and the design process can progress to the "domain-specific embodiment design" phase. In the next step the system has to be divided into different modules including the interfaces between them and responsibilities have to be assigned to the different domains or teams. In order to support this partitioning both the function structure and the system model can be used. Especially the latter has several benefits since it represents the system structure and the connections between system elements. The structure of the system including modules and interfaces is shown in Figure 9. Based on this structure and the information from the previous stage Analysis Milestones have to be further detailed.

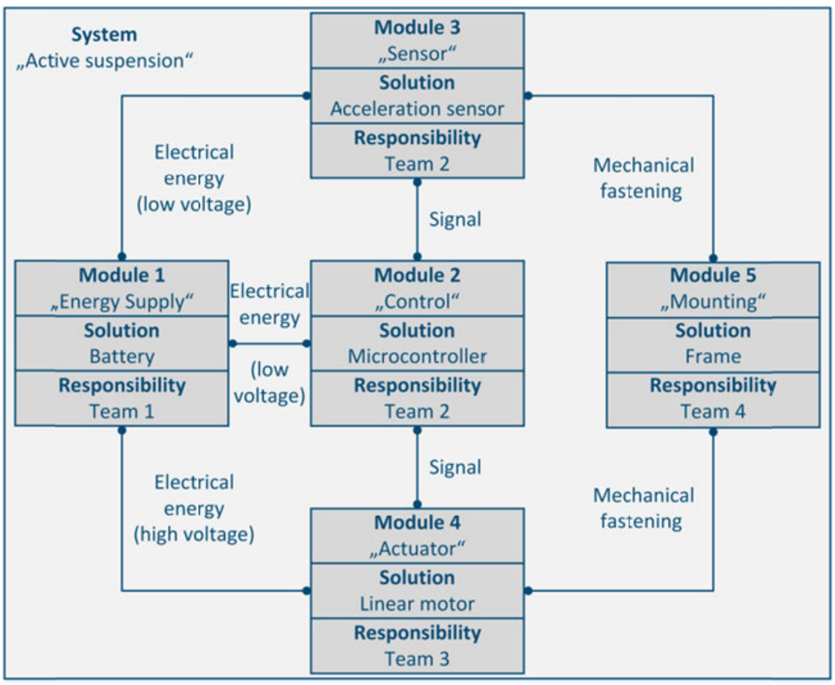

Figure 9. System structure including modules and interfaces

5. Discussion

The example of the development of an active suspension for bicycles that has been presented in this paper is used for the validation of the authors' simulation-based framework for mechatronic design.

The central aspect of the framework is the process model consisting of two parallel streams which are intended to enable simulation as continuous action in parallel to design. This separation has proven to be very helpful for the comprehension of the numerous micro-iterations between design and simulation.

The concept of Analysis has been successfully applied. Although it is sometimes difficult to define a preliminary set of milestones prior to design, it is helpful in structuring the process. Especially during analysis-synthesis-cycles the milestones provide support for the management of iterations. Furthermore they contain all relevant information for a specific analysis in one entity which makes it much easier to handle information.

One problem of Analysis Milestones has become obvious during the validation: the chronology in which the milestones should be processed within a specific design phase is not clearly expressed in the current form – only through the counting index which for example cannot express parallel milestones.

One possibility to improve this issue is to subdivide each development phase into smaller segments and assign the milestones to those segments. In this way they could also be graphically arranged on a timeline, also in parallel if necessary.

Another issue is that most of the milestones are processed several times during the development process, generally becoming increasingly detailed. In order to keep track of the milestones and hence of the entire process, it would not make sense to create new milestones each time. But just giving an index which indicates the iteration is also not sufficient, for example because of traceability.

In the current paper-based way in which Analysis Milestones are written and managed, a consistent description and linking of the individual milestones is not possible and hence clarity is lost. A database-centered approach would be much more practical and could for example be directly linked to requirements management tools.

Another aspect which became apparent during the validation example concerns the different use-cases for simulation: on the one hand it can be used to check if the required properties can be reached with a specific design concept – which means with a defined set of characteristics. But on the other hand simulation can also be used to derive properties from other ones, e.g. the required forces and speed for the actuator in the presented example. At the moment this aspect is only implicitly covered in the framework. It might be useful to distinguish within Analysis Milestones if the analysis is used for the first or the second purpose. The derivation or refinement of properties – which in this case is equivalent to requirements – requires other aspects than the pure analysis of an existing design which would lead to a different structure of the milestones.

Related to the aspect mentioned before is the management of changing requirements. Currently those changes are not explicitly covered in the framework but have turned out to be very important and their handling can be supported by the use of simulation. Hence they should be further considered in the framework where requirements are depicted more or less static at the moment and are not part of the iteration cycles yet.

Especially in early phases – like in conceptual system design in this paper – knowledge about the system is rather low. Hence parameterization of a simulation models is difficult because the relevant information is not known yet, or at least only roughly. This leads to a higher degree of uncertainty of simulation results in early phases which has to be considered.

Related to the uncertainty of parameters is the decision of modeling depth. There always has to be a trade-off between modeling depth – which in general corresponds to the accuracy of simulation results – and the time and capacity spent for modeling. Especially in early phases the choice of modeling depth also depends on the knowledge about the system and hence about the parameters required for the model. At this point support for the choice of suitable models and simulation tools is needed.

In the context of this paper a domain-spanning simulation environment based on the Modelica language has been used and has proven to be well-suited for application in conceptual system design. It offers the possibility to model contents of different domains and uses their specific symbols and notations for the graphical representation. Hence all involved designers understand the modeled system and its structure. Furthermore model libraries are provided which speed up model generation and also support in finding working principles to each subfunction of the system. As a results of this, the system can be directly simulated which supports the concept of micro-iterations between the two activity streams in the process model.

6. Conclusion and future work

In this paper a simulation-based framework for mechatronic design is validated on the example of an active suspension for bicycles. The focus is set on the conceptual system design phase.

This example shows that the use of simulation as a central design technique in the early conceptual design is a useful way for the development of successful systems. Besides just analyzing and hence improving design, simulation has also proven to be very useful to increase knowledge about the system. The framework has offered adequate support for the use of simulation. Some minor issues occurred during the validation project which still have to be addressed. One of these is the structure of Analysis Milestones which will be improved prospectively. Furthermore the fact of changing requirements has not been explicitly integrated into the framework yet. A third aspect is parameter uncertainty which is particularly important in early phases when system knowledge is rather low.

Future work will focus on the improvement of the identified issues. Furthermore the active suspension example will be used to validate the framework also in the later phases of the design process, i.e. in domain-specific embodiment design and system-level integration. The basis for this has been set by the partitioning of the system into modules and interfaces (see Figure 9). In those phases also the CPM-based description of the process will be validated.

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