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Perspectives on hierarchical modeling in mechatronic design ☆

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ABSTRACT

Hierarchical modeling helps to describe product models and data from different viewpoints that, representing the different disciplines involved in the design process of mechatronic systems. This paper gives an overview of hierarchical modeling techniques. This includes the investigation of systems, which requires handling different issues that address very specific views of the system (system aspects) and come from various disciplines. Also the model granularity which describes the extent to which an object or model is broken down into smaller elements it an important aspect. The different phases of the product life cycle require models with different objectives and levels of detail. Some models are needed mainly in specific phases of the product life cycle, which are discussed in detail in the paper. Especially in the conceptual design phase some design-characteristic aspects such as hierarchy of parameters, modularity of the design should be analyzed, because in this phase the largest part of the later resulting product costs is predetermined or even fixed. As a consequence, the scope for design is limited to merely small changes in the subsequent design phases. Therefore the interaction between the design phases and the related models plays an important role the development process of mechatronic systems.

1. Introduction

Mechatronics is an engineering science based on the classical disciplines of mechanical engineering, electrical engineering/electronics, and information technology. The defining characteristic of mechatronics is the integration of these domains throughout the whole design process. The design of embedded systems such as intelligent sensors and communication and power systems must be integrated into the mechanical design, developed, maintained, and recycled. As software and hardware platforms change due to new technologies and new technical interfaces emerge, new challenges arise in research and development. Interaction between product developers from different disciplines is impeded by insufficient understanding between the disciplines and by a lack of common platforms for modeling (and simulating) complex systems. Domain-oriented partial solutions will generally not provide the optimum result for the integrated system.

When a mechatronic system is designed, the mechanical equipment can be devised before control system design begins. An obvious drawback of this sequential approach is the lack of compatibility between the subsystems, which results in additional effort and costs to meet the specifications of the overall system. Another drawback of this approach is that, in the course of the design process, the decision must be made whether a mechatronic or a merely mechanical solution is to be used. Designers must coordinate mechanical and electronic solutions in order to find a suitable overall solution. Here, not only the selection of materials and the knowledge of process constraints in terms of the geometry of parts play a role, but also the selection of completely different working principles from different domains. Clearly, designers need support in their increasingly complex and multidisciplinary task in order to rapidly review alternative solutions during the design process and to facilitate the correct choice [6,2].

The design of the product model should consider the requirements of modeling mechatronic systems. An undeniable precondition for successful product development is the availability of an interdisciplinary definition, description, and presentation of product information. Product models must map reality to a significant representation in order to make valid predictions. Relevant phenomena/aspects such as geometry, kinematics, dynamics, stability, materials, electrodynamics, saturation effects, capacities, controllability, observability, cycle time, and memory are included. These can be represented in various computer-aided model descriptions such as sketches, drawings, diagrams, layouts, schemes, flow charts, reports, specifications, pictures, data structures, equations, and inequalities. For this purpose, specific design views must be derived from an overall model. Generally, such an overall model will be less sophisticated than more detailed sub-models for one

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specific aspect. From this point of view it can be concluded that models should cover both the different views of a system and the different degrees of detailing. Nevertheless, all these models (for different views and at different levels of detailing) should be as consistent as possible with each other.

In this paper we consider the following research questions:

- What are appropriate hierarchies and granularities for models of mechatronic systems?
- How can the dependencies between discipline-specific and system models be described?
- How can consistency of models from the different disciplines be guaranteed in the overall product development process?

2. Background on hierarchical modeling techniques

This chapter gives an overview of hierarchical modeling techniques starting with the functional design phase.

2.1. Function-oriented design

A conceptual design method called function-oriented design (FOD) was developed within the iViP (integrated Virtual Product Creation) project [20]. It focuses on product functions (see also Pahl and Beitz [23]) as the central component when developing new products or modifying existing products.

From the systems engineering point of view, a technical product can be modeled as a system described by its function and the interactions with its environment, using only input and output parameters. The system's function can be structured hierarchically into subfunctions, thus describing it at different levels of abstraction. The advantage of this approach is that finding solutions becomes simpler (due to the reduced complexity of the subfunctions), documentation is facilitated, and reusability of product components increased. Since functions alone are not sufficient to describe a system, they are supplemented with requirement definitions, system structure (its components), and constraints that link these three aspects. Additionally, conventional geometric CAD data is integrated to support the detailed design phase. To ensure product quality superior to that of conventional design strategies, total quality management (TQM) methods (e.g., quality function deployment, QFD) can also be included. In contrast to standard TQM methods, FOD allows these methods to be implemented at the object level (i.e., for every subfunction). Further benefit can be drawn from defining tests along with the requirements such that design consistency can be checked at every point in time. This method has been implemented in a software system called FOD, which includes four separate editors for product requirements, function, structure, and constraints. To retain compatibility with modern design processes, interfaces to different CAD systems have been implemented which provide FOD with the ability to link product function to geometry. Model reuse is supported through an integrated component library, and the product constraints can be solved using a constraint solver.

2.2. Level of abstraction

The top-down principle of systems engineering works explicitly with different levels of abstractions. The system or system components are viewed as black boxes with connections to other elements and to the context of the system [5]. At a more specific level, the black boxes become clear and contain white boxes containing numerous technical details (see Fig. 1).

Abstraction levels are an important topic in systems design. Clearly separated levels of abstraction with consistent relations

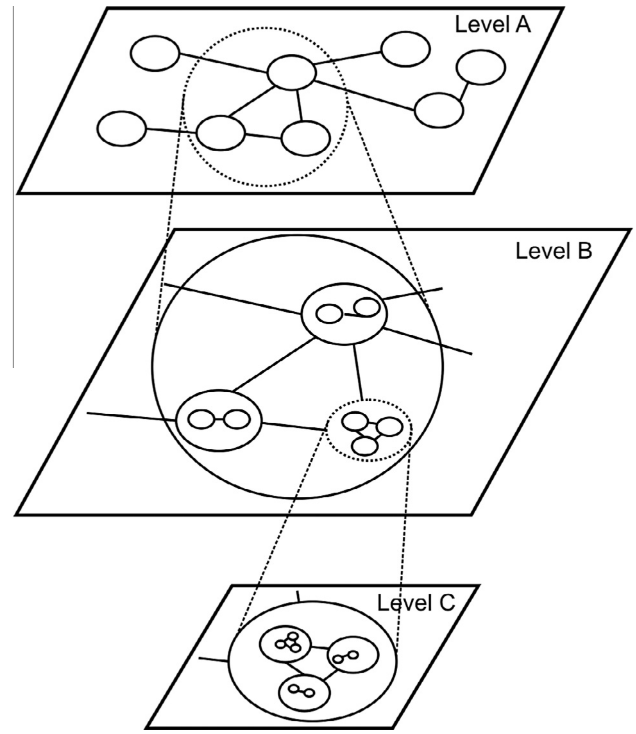

Fig. 1. Levels of abstraction [4].

between them are indicators of good design. [4] proposed three modeling levels for systems in engineering design:

1. A high-level model for documentation, communication, and project management,
2. Low-dimensional models that form a general simulation frame, and
3. High-dimensional models for the low-level parts – using concepts such as finite element models.

Levels of abstraction are used mainly in basic engineering in order to capture the functional structure of the entire system or subsystem. In the context of this paper the overall mechatronic design is addressed at higher levels of abstraction. At lower levels of abstraction (see [4,14]) discipline-specific models may be used to provide a white-box view. Since functional decomposition typically occurs at higher levels of abstraction, the lower levels of abstraction provide a discipline view only for a specific function or part of the system, not for the entire system. Brunetti and Golob [3] presented a feature-based method for describing product models especially for the conceptual design phase. The approach is based on the interaction between feature and part models.

2.3. Architectural model

Alvarez Cabrera et al. presented an architectural model to support cooperative design for mechatronic products [1]. They focus on the conceptual design phase using an approach similar to the V-model. The model is decomposed into different architectural levels (see Fig. 2) which help to illustrate the links between requirements and functions.

2.4. Model-based perspective

Qamar et al. ([24,25]) introduced a method for designing mechatronic systems with a model-based perspective and