Semantic Information and Process Modelling in Mechatronic System Design

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Abstract – This paper presents a novel model based design process for mechatronic systems. The process is based on VDI 2221 and VDI 2206 principles and compatible with systems engineering management. The process presented consists of clear recursive and iterative phases which each provide formal and interoperable outcomes which enable efficient ability to re-use and re-cycle designs. Even though the process is model based it is tool-independent and promotes using best suited engineering and design tools for each domain. The process is supported by semantic product data management utilizing semantic product lifetime data model. Semantic data management enables numerous benefits such as automatic design re-validation on requirements changes, data interoperability and interoperability of models of various domains and efficient system of systems level model generation. Process also allows each engineer to work on his/her comfort zone but to share the vision of all others working on the same project as well as the big picture on the final product which leads to better design quality and products better meeting customer requirements.

I. INTRODUCTION

Systems engineering approach is probably the most widely accepted underlying theory for managing large scale multi-domain engineering operations. Over recent decades application of it has spread widely in various industries because it can provide a feasible structure for solving multi-domain design problems and coordinate design efforts. It also offers possibilities for whole life cycle integration which involves customers in the design process and ensures that the systems developed are viable throughout their life cycles. However being merely a theory of engineering management systems engineering does not offer practical design or engineering processes or solutions. [1] [2]

Formal processes and methods for engineering and design are essential for systems engineering to be an applicable approach with modern complex cyber-physical multi-domain systems. Formal process and method base applied to multi-domain engineering and design processes also offer benefits in terms of promoting innovation by strengthening collaboration and co-creation, improving information interoperability, improving design quality and enabling more agile and flexible engineering operations. Formal process base utilized in engineering and design also enables company or organization fully utilize engineering intelligence methodology and to operate efficiently and agilely as a part of engineering intelligence ecosystems [3].

Engineering and design process models applied in practice today stem mostly from German VDI 2221, VDI 2422 and VDI 2206 standards. Each of these standardized models have their own shortcomings and constrains which limit their applicability. VDI 2221 is traditionally seen concentrating only on mechanical systems which has limited its application and on the other hand VDI 2422 concentrates on microcontroller control which limits its applicability. VDI 2206 offers the best multi-domain engineering and design perspective and it is thus its macro-level design process V-model is in many occasions misleadingly seen as a depiction of a systems engineering process. However the infamous V-model is essentially just a rearranged VDI 2221 waterfall model and a V-shape is used to describe the relationship between management, design and test activities. [4] [5] [6]

Misinterpretations of process models are commonplace. A common mistake related to the waterfall model is that each phase requires completion of the one before it can begin. Another common mistake is to forget that the V is only an overview of some of the aspects of the project cycle relating to development and test/evaluation at the various phases of the system life-cycle. Therefore V-model cannot be seen as a process model and its simplistic straight forward use often leads to inability to prevent design defects and failure to react to changes requirements during development.
II. HISTORY OF DESIGN PROCESSES

Design processes have been studied for at least past five decades and these studies have led to development of various guidelines and process models. This chapter will introduce the relevant process models that have contributed and influenced in VDI 2221, which also is the basis for the Semantic model based design process introduced in later chapters of this paper.

EARLY THEORIES BY KESSELRING AND HANSEN

The first theory invention process was developed by Fritz Kesselring in 1954 [7]. In his book Technische Kompositionslehre he describes an invention process based on his own practical experiences. His aim was to identify preconditions, operations and steps leading to successful invention and externalize them as a theory. The process he proposed consisted of aspects which are common to all invention processes. The process was directed to an individual designer and it concentrated on thinking and working processes which were based on associations and analogies. Freeing oneself of prejudice and existing solutions is emphasized.

In 1965 Friedrich Hansen introduced his theory in his book Konstruktionssystematik [8]. The theory was based on the system which consists of relationships between the development process tasks and requirements and successful solutions. According to Hansen there are always certain patterns involved in the development process and they form a foundation for logical sequences of thoughts and actions. The purpose of the process was to guide a design engineer to think logically and proceed systematically. The process is directed to an individual designer as well as an engineering team. Hansen’s process emphasizes on the necessity for iterations and it even has a separate step for failure criticism to offer a possibility to improve existing solutions.

VDI 2222 PROCESS

Standard VDI 2222 Konzipieren technischer Produkte was first published 1973 [9]. It bases mostly on proposals made by Kesselring and Hansen and was published by VDI (Verein Deutscher Ingenieure - Association of German engineers). VDI 2222 was intended to be a practical process for developing technical products but also a contribution to education of design engineers. The scope was to provide a process which is valid from mechanical to electrical engineering.

The process is based on problem-solving sub-processes. One central idea of the process was to assign distinct design methods to each individual design phase. The process has four main design phases: Clarification of the task, conceptual design, embodiment design and detail design (Figure 1). After each step, is made a decision of whether to proceed to the next step or to repeat previous step.

The process has special attention on iterations and adaptation of the requirements specification during the complete design process.
In 1993 the VDI 2222 standard was replaced by the VDI 2221 *Systematic approach to the development and design of technical systems and products*. Upon introducing VDI 2221 VDI 2222 was also updated to two part general problem solving and design methodology standard [10] [11].

The process is still based on old VDI 2222. The target is to propose a general methodology for designing technical systems and products and to support a methodical and systematic designing. The process is independent of the domain and addresses only content and organizational aspects of designing work. The basis of process lies in the theory of systems engineering. One main difference in between VDI 2221 and old VDI 2222 is emphasis on the integral data processing and the application of CAD in VDI 2221. Figure 2 shows the flowchart of the VDI 2221 process.

**Figure 2 VDI 2221 process [5]**

**DIRECTION OF EVOLUTION**

Four theories and processes introduced in previous chapters show the evolution during three decades. There has been comprehensive change in the basis of theories and processes as well as in the nature of directions, advices and instructions they provide. Also the common terminology for this field was developed during these three decades.

Kesselring based his theory to his personal experiences and targeted the process for an individual engineer. Hansen gathered wider experience base than only his personal experience and also developed process more for a team than an individual designer. VDI standards are products of combined scientific and practical experiences of larger workgroups.

There is also a fundamental difference in the scope of these theories. Kesselring simply transformed procedure and incidences related to his inventions into a process. Hansen established his theory to systems idea and methodological thoughts. The VDI standards focus more and more on the holistic systems engineering based approach. The overall focus of theories and processes has changed from support for an individual engineer (Kesselring) towards generalized engineering procedure for a company addressing both organization and content of a design or development process (VDI 2221).

During past decades theory of engineering designing has moved to the level of scientific theory. Also demand for generalized process for different domains of engineering design have mainly been realized by the abstract terminology and formulation of logical processes used in current theory. Demands on design engineers, whose daily work is affected by these theories, have also been increased. They need to have a holistic and comprehensive view to the design process to have an adequate understanding on process flow and design requirements.

Earlier theories and processes seemed easier for a design engineer to understand and to apply. This partly caused by the fact that they are products of simpler times – during past decades development from mechanics to mechatronics and from embedded systems to cyber-physical systems has considerably increased complexity of the world where design engineers work daily. Changes and improvements in theories of design and practical design processes have caused acceptance and application problems among industry. Besides increased complexity of design theory itself acceptance and application difficulties also originate to difficulties to effectively and seamlessly apply modern engineering design tools to practical design process. These difficulties are caused by the vast speed engineering design tools, especially modelling and simulation tools, develop nowadays and the fact that even the most modern design theory dates back times before emergence of efficient model based design
tools. Integrating engineering tools to each other and on the other hand to the flow of the design process so that interoperability and reusability of results can be guaranteed is of utmost importance for efficient utilization of any design process.

Utilization of semantic web based tools and semantic data modelling in processes related to mechatronic machine system design has been studied and they have been found to bring promising possibilities available [12] [13]. They enable interlinking various design and management tools used in different stages of design process to each other and also guarantee integrity of data produced and thereby enable true interoperability and reusability of data. However to fully utilize them the design process must tailored to fit their usage and also to fit model based systems engineering principles [14].

III. SEMANTIC MODEL-BASED MACHINE SYSTEM DESIGN PROCESS

Semantic model-based machine system design process is an engineering design process for model based systems engineering with semantic product data management systems. It is main structure is based on VDI 2221. Process flow is waterfall and it has same iterative and recursive qualities as VDI 2221. It is compatible with the V-model process presented in VDI 2206 (Figure 3) – semantic machine system design process forms the left hand side branch of V.

Its compatibility also extends to W-model (Figure 4) which is enhanced V-model introduced to improve some of short comings and unclarities related to V-model [15] [16].

In semantic machine system design process each process phase produces well defined rich formal information which is stored in Semantic Product Lifetime Data Model (SPLIM). SPLIM is in the semantic data management system which is capable to store, enrich and serve semantic product information. Each process phase utilizes information produced by earlier phases and stored in SPLIM.

PROCESS OUTLINE

Like VDI 2222 and 2221 processes the semantic model-based machine system design process also has four main phases: Specification, conceptual design, detail design and documentation. Main phases divide to seven more specific subphases (Figure 5).
Each subphase utilizes information served by semantic data management system containing SPLIM and produces outcomes which are then stored there. Since the process is model based process outcomes are mainly models (mathematical deterministic and stochastic models, conceptual models etc.) and their parameter sets. Model structure is hierarchical so that each model produced links the model produced in the next phase in higher level requirements and complete model hierarchy links all individual design parameters to topmost level requirements (typically customer requirements). Semantic information management system has an ability to automatically produce adaptive views to product information and thus design and other documentation related to product can be automatically produced by it.

**SPECIFICATION PHASE**

In this phase the task is further defined. Definition is extracted from parent process requirements, customer requirements etc. The key target is to interpret partly conceptual task definitions and requirements to exact engineering specifications.

Specification phase has two outcomes (Figure 6). First of all it produces requirement specification, which is a fundamental technical definition of the system containing exact technical specification of it. Secondly it also produces an allometric model of the system, which is a mathematical model of the requirement specification. I.e. it mathematically describes relations between design parameters and customer requirements such as: Power to weight ratio, specific fuel consumption, net weight / gross weight etc.

**CONCEPTUAL DESIGN PHASE**

Conceptual design phase contains three subphases, which all have individual and separate outcomes (Figure 7). The first subphase designs the function structure of the system. Function structure defines logical functions and static relations related to the system. On the other hand it also defines the conceptual model of the system. Conceptual model is a simple black box
describing static relation between system input and output. Relation is typically modelled as logical or statistical dependencies. Model may also include some disturbances if they play an important role in the system.

Search solution principles subphase defines solution principle for the system. Solution principle defines material, energy and information functions and their static and dynamic relations. On the other hand it also produces conceptual model. Preliminary model is a simple black box type mathematical model describing dynamic relation between system input and output. It includes disturbance and process models at the level they are needed in this phase. Typically it is a dynamic lumped parameter model.

The final subphase divides the system in parts or modules which are manageable in design process as well as in production of the final system. In this subphase the solution principle of the system decided. The solution principle defines physical and chemical effects which enable desired functions of the system and also operation principle according which the system will work. Model produced by this phase is distributed component or element model, i.e. it contains separate component/element/subsystem/process models. Typically it is a system of dynamic lumped parameter models. All models at this stage are domain specific.

**DETAIL DESIGN PHASE**

The first subphase of detail design phase (Figure 8) produces preliminary system design. It contains modular layout, i.e. division to components and/or separate design elements. In this phase design process is divided in parent and child processes according to modular structure of the system. Child processes are initiated and their design requirements are supplied to them. Model produced is a detailed distributed parameter physical model which can later integrate, interact and exchange parameters with usually domain specific models produced by child processes.

The second subphase produces the final design proposal. In final design proposal all child processes are integrated into parent process and complete design is validated against top level (typically customer) requirements.
**DOCUMENTATION PHASE**

Documentation phase (Figure 9) prepares all information for producing adaptive views which can be used as production documentation, assembly instructions, user documentation, maintenance documentation etc. It also verifies the final system model and all its submodels against prototype testing data and finishes the model to be used as a tool in life-cycle, systems integrity and other services.

![Diagram](image)

*Figure 9 Flowchart of the detail design phase*

**IV. CONCLUSIONS**

Semantic model-based machine system design process is especially developed to tackle with challenges set by ever increasing complexity of modern day cyber-physical machine systems and also to fully utilize potential of modern engineering design tools. It is based on well-known and thoroughly proven VDI 2221 and 2206 processes and thus its utilization does not require any organizational or other fundamental changes.

Main benefits achieved by utilizing this design process methodology are:

- The process has clear phases and subphases making it formal, but yet easy to follow and iteratively develop further, which makes it easy to understand and adopt.
- Process and methodology is tool independent.
- Ability to efficiently re-use and re-cycle designs
- Because of formal process and minutely stored formal outcomes there is no need for reverse engineering to understand why something is designed the way it is
- Because of hierarchical model structure all re-validations of new or changing requirements or design parameter changes can be automatic.

However the biggest advantage is that this can lure an individual design engineer to peek out his own silo without leaving his/her comfort zone. By peeking out he/she is able to see and share the vision of all others working on the same project and what is most important: The big picture behind all – customer requirements.
V. REFERENCES


