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MECHATRONIC DESIGN – HISTORICAL BACKGROUND AND CHALLENGES FOR THE FUTURE

Stefan Moehringer
Simon Moehringer Anlagenbau GmbH

ABSTRACT
The cross-linking of mechanical components by means of electronics and information technology goes unstoppably forward. New functions, more safety and comfort - mechatronics opens success potentials. The complexity of mechatronic systems grows, however, in the same breath, interactions get more multilayered and the shorter development times increase the development risk.
This paper focus on mechatronic design: it starts with an overview on the historical background of mechatronics. The evolution of mechatronic shows the enlargement in disciplines (heterogeneity) and the increase in complexity. But the methodology is still based very much on mechanically dominated products. The challenge for the future is to support the designer with new methodologies which are able to handle the increasing complexity and incorporate the design requirements of smart mechatronic systems. Examples of new functions and products are illustrated.

Keywords: Mechatronics, Design Theory and Research Methodology, Strategy

1 INTRODUCTION
A sensor in the outside mirror recognizes raindrops on the windscreen and passes the information on to the braking system. By regular easy touchdown of the brake blocks these are kept dry which leads to a significant reduction of the braking distance. A camera supervises traffic signs and the distance to the vehicle driving in front and displays warns of speeding to the driver via head-up. A dangerous short distance automatically leads to an emergency stop.
These innovative examples of new functions are no fiction any more. They become reality in modern vehicles of today. The intelligent combination of sensors, actuators and control systems allows innovation steps which have been hardly imaginable. According to a study of McKinsey & Company the electronic share in the motorcar will increase from currently 20% to approx. 40% in the year 2015. Traditional mechanical components will be cross-linked with electronics and information technology. The X by-Wire technologies for the braking and steering system will be introduced until there.
Mechatronics - the synergetic combination of the disciplines mechanical engineering, electrical engineering and information technology - opens considerable success potentials; not only for the technology leader automotive industry but also in mechanical engineering and related industries.
These fascinating possibilities raise the question whether existing methodologies are able to support the mechatronic design process. Where are we today and which are the challenges in design of tomorrow?
This contribution gives an overview on mechatronic design. The early beginnings of mechatronics and its evolution are explained, the key research areas of today are outlined and an outlook to future challenges is given.

2 HISTORY OF MECHATRONICS
What does Mechatronics mean? The opinions what mechatronics is rather differ far: Hewitt thinks, for example, that an exact definition of mechatronics is neither possible nor desired; in view of the rapid development a firm definition only would limit this development dynamics [1].
The role of mechatronics as a discipline is also judged differently: The one regard mechatronics as an independent discipline with fascinating possibilities, the others see mechatronics as an intelligent combination of existing disciplines [2].

A generally accepted, uniform definition of the term mechatronics is not recognizable. In order to get a better understanding we will have a closer look to the early beginnings of mechatronics.

2.1 A Young Discipline

The young discipline mechatronics has been mainly influenced by the design methodology of mechanical engineering which has a long tradition. Since the first concepts published in the forties a comprehensive methodology of engineering design has been established (see historical look back in [3]). The two guidelines VDI 2221 [4] and VDI 2222 [5] bundle different methodical approaches of the seventies and are internationally known as procedure models for the product development.

Mechatronics started to enrich the so far mechanically dominated engineering design. In 1969 the Japanese Ko Kikuchi, president of YASKAWA Electric Corporation, formed the term Mechatronics [6]. The manufacturer of automated technical products, like servo drives and robots, understood mechatronics as the electronic function expansion of mechanical components. The term consists of ***Mecha**nism* (later mechanics, or general mechanical engineering) and ***Electronics*** (electronics or general electrical engineering) and was protected in the period from 1971 to 1982 as a trade name [7].

2.2 Evolution of Mechatronics

While mechatronics was originally only a functional enrichment of mechanical components the fast growing technologies of microelectronics and in particular the microprocessor technology enlarged the possibilities.

In figure 1 the evolution of the term mechatronics is shown by major definitions. Schweitzer [9] has seen the information technology as the third discipline integrated by mechatronics. He defines mechatronics as all forms of sensors, actors, electronic functions and mechanical system components in an integrated functional of spatial arrangement.

The next evolution step was formed by Harashima, Tomizuka and Fukuda in 1996 [6]: "Mechatronics is…the synergetic integration of mechanical engineering with electronic and intelligent computer control in the design and manufacturing of industrial products and processes". Mechatronics accordingly relates besides functions and components as well to the integration of design and manufacturing. Key of this understanding of mechatronics is the synergetic effect of different disciplines. New functions can only be realized if mechatronic design considers the integration of technologies starting from the very early design phases.

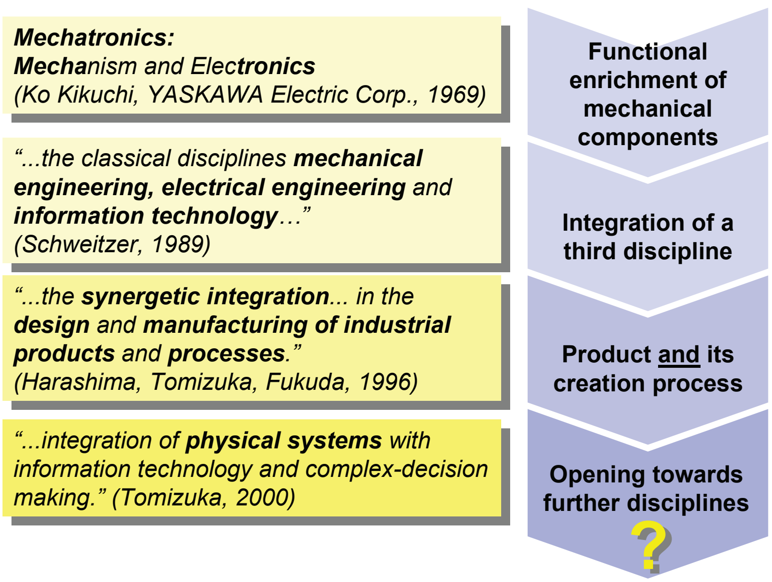

Figure 1. Evolution of Mechatronics

The last important milestone is the opening of mechatronics to physical systems: mechatronics does not necessarily need a basic system with a mechanic structure. Any physical system e.g. biological, chemical is conceivable to build a mechatronic structure in combination with electronic and IT function elements. In 2000 Tomizuka [9] formulated this definition so broadly that any industrial products and processes can be subsumed under the term of mechatronics.

2.3 Mechatronics today

It is the question whether mechatronics in the general understanding has already fulfilled this opening towards physical systems. But there is no doubt that mechatronics is characterized by a multi-disciplinary dimension. Mechatronics consequently uses the synergies from interaction between the classic engineering sciences mechanical engineering, electrical engineering and information technology (Figure 2).

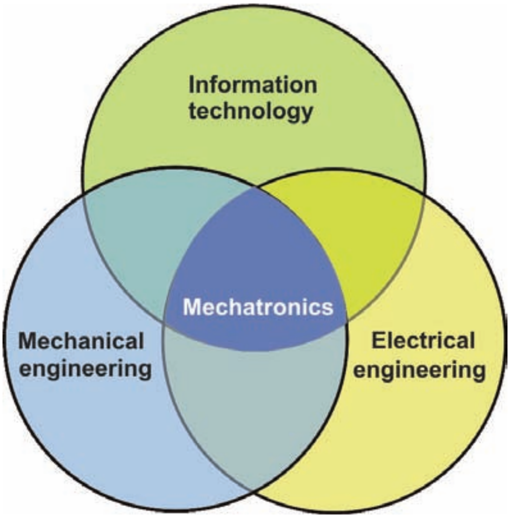

Figure 2. Mechatronics – synergy from the interaction of different disciplines [10]

This interaction between engineering domains opens success potentials for new products and applications (figure 2-4). These can be subdivided into four areas:

- Function and behavior improvement in technical systems
- Reduction of size, weight and costs
- New functions and applications
- Smart and self-optimizing systems

Function and behavior improvement in technical systems

Mechatronics contributes and to improve functions and behavior of existing technical systems. The outer phenotype, the principle functioning and the application field usually stay with it unchanged. Examples of such success potentials are:

- Improved positioning accuracy by compensation of mechanical insufficiencies within industrial robots
- antilock braking system (ABS) - the basic concept of the hydraulic braking system is supplemented by antilock valve, speed sensor and control unit to prevent a locking of the wheels
- dynamic steerable headlight: the headlight is steered in relation to the curve radius and the driven speed; the driver recognizes the curse of curve earlier and can adapt his way of driving

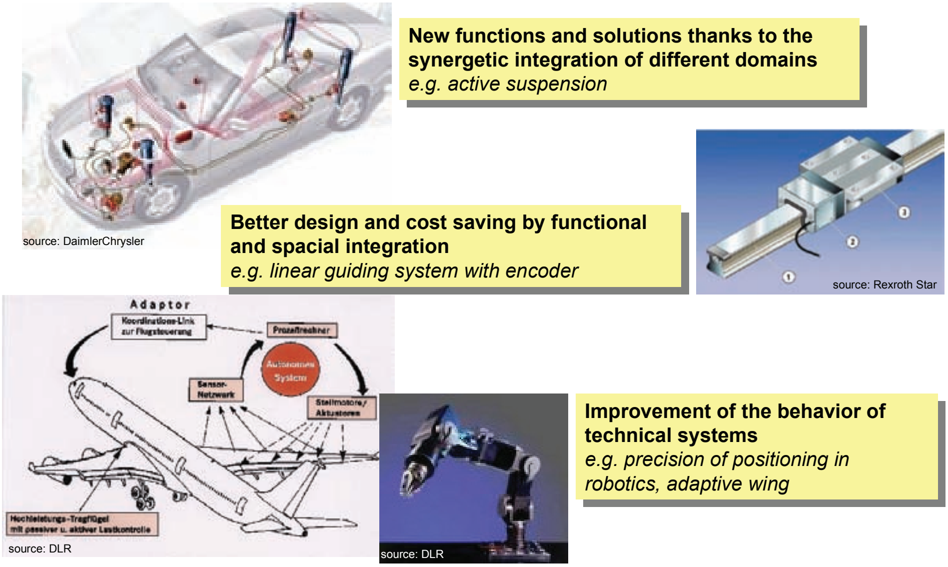

Figure 3. Examples of success potentials in mechatronics

Reduction of size, weight and costs

Particularly by the spatial integration size and weight of components can be reduced. This can be realized by integration of electronic functions into mechanical elements (connector or case) and by the design of multifunctional components (cases, cooling body and cable bracket). Modern structural design and packaging of integrated circuits e.g. flexible circuit boards, insert techniques play an important role.

New functions and applications

Completely new functions and applications can arise if systems are conceived from the beginning in a “mechatronic way", i.e. they are based on the synergetic combination of solution principles from different domains. Examples are x-by-wire applications in the aeronautics or motor industry; furthermore material structures which integrate sensors, actors and information-processing components and take over load-bearing as well as actuatory or sensory tasks simultaneously (piezo-electric systems).

Smart and self-optimizing systems

New research and fields of application arise with so-called intelligent (smart, active) mechatronic systems. This means the ability of a mechatronic system to recognize its internal conditions and to optimize these with the help of an inherent information processing. Examples are machines with self-diagnostic capabilities, i.e. they can adjust themselves, give information about operational safety and rest life time and suggest corrections (unbalance correction of active magnetic bearings).

3 KEY RESEARCH AREAS IN MECHATRONIC DESIGN

A detailed description of key research areas in mechatronic design can be found in [11]. In the following recent research activities are focused and illustrated in figure 4.

3.1 Overview on Key Research Areas

The overall and predominant theme is complexity. It is concerned in terms of the large solution space, in terms of the number of components interlinked and in terms of designers from different domains working together. Three different research directions can be structured starting from the term complexity: Design methodology, design automation and self-optimizing/cognitive systems.

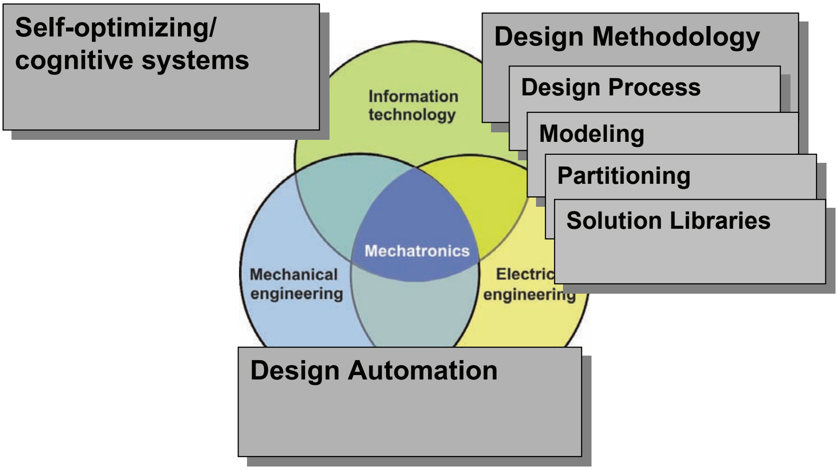

Figure 4. Key Research Areas in Mechatronic Design

The main topic is the design methodology. The design process can be supported by a 3D visualization of mechatronic system structures which allows an overlapping of the product and its involved domains and the associated development process. A transparent visualization of design dependencies helps to handle complexity [12]. The use of UML diagrams to represent structural and behavior models of mechatronic systems is investigated [13]. Aim of partitioning is to allocate the functions to working principles and solutions elements of different engineering domains in order to achieve an overall system optimum. Within mechatronics this allocation is more complex due to the large solutions space and the iterations between components to be considered. A heterogeneous modeling approach can support the partitioning [14]. Design iterations are necessary in order to find the overall optimum, but time-consuming and cost-intensive as well. A classification of iterations and an approach on the control helps to avoid unnecessary iterations [19].

Design automation is another key area to deal with complexity. The idea is to handle the increasing number of possible solution combinations with the help of computational design synthesis [15], [16].

Third key area deals with self-optimizing and cognitive systems. These systems with the ability to react to changing environment have an inherent strategy to handle complexity. The vision is that not only the designer but also the system has an overall goal of its behavior. The behavior can be changed and adapted to new conditions. Coherent partial models are proposed to specify environment, application scenarios, requirements, functions, active structure, system of objectives, behavior and shape [17], [18].

3.2 Detailed Research Review in Design Methodology

If we look deeper into the recent research activities in design methodology we can analyse the level of completeness. We will raise the questions: which design phases are covered? Does the methodology support the designer on a generic and procedural level (makro level) or as well on a specific and detailed level (micro level)? Which are new research topics? Which are open areas?

For this analysis we classify the research activities in two dimensions: the design phases from conceptual design to detailed design and the design view (from generic to specific). The following figure (see figure 5) shows 16 important research activities classified.

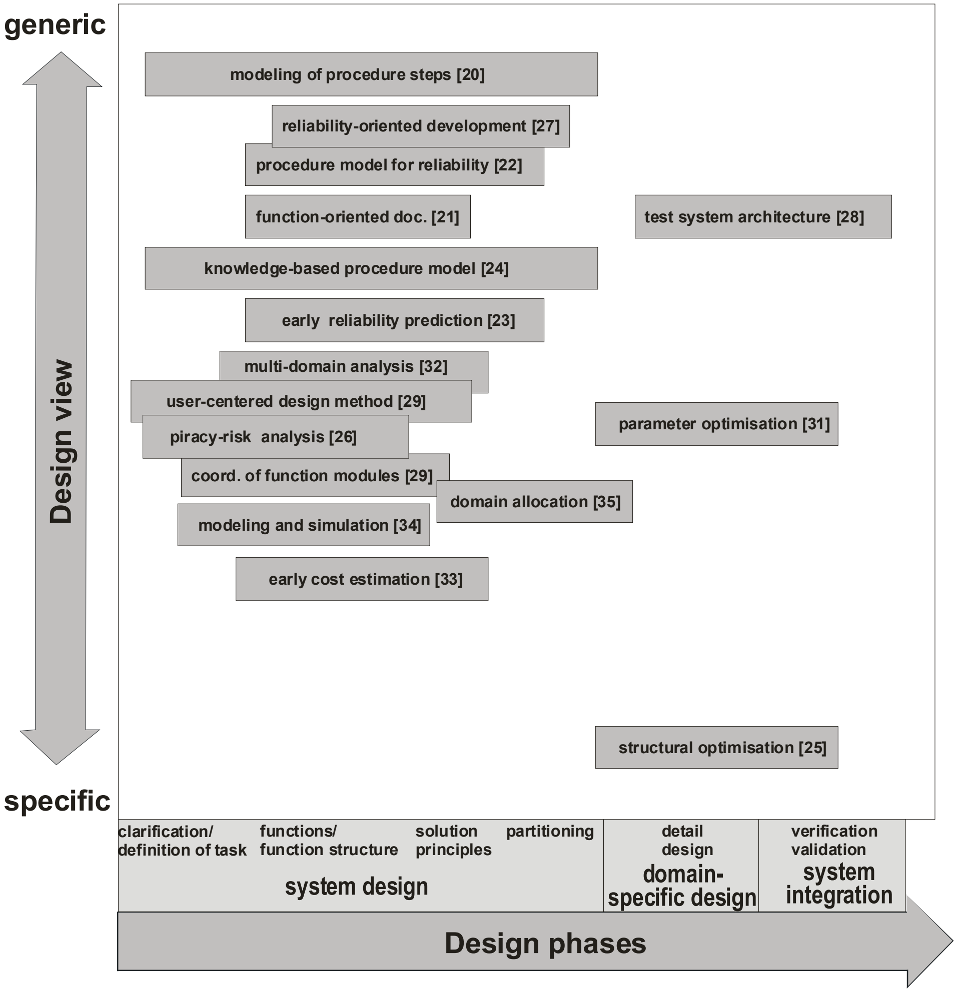

Figure 5. Classified research activities in Design Methodology

This leads to the main findings:

- **Concentration on Conceptual Design**: The majority of the research work focus on the early phases of product development. There are only 3 papers dealing with aspects of detail design and tests.
- **Functions – solution principles predominant**: Within the conceptual design the function structure and the searching for solutions principles are in the focus of interest. The aspects of requirements or the partitioning into specific domains are not taken into account in most of the works.
- **Overall approach is missing**: A methodology closing the gap between the early conceptual design and the verification of the design results cannot be found. To deal with incomplete information during the early phases and to handle the heterogeneous information with increasing product maturity seems to stay an unsolved problem.
- **Focus on generic approaches**: Most of the contributions help the designer to organize design procedures and to manage information on a generic level. Only the minority provide specific methods to analyze structures and interdependencies or support for synthesis.
- **New topics**: Recent research activities can be found in reliability and piracy risks. Reliability is a very important subject as the acceptance of more and more sophisticated, mechatronic products is

strongly related to reliability, e.g. assistant systems in the automotive or house-keeping robots [22], [23], [27]. The piracy risk is on one hand increased by global information linkage and wireless networks. On the other hand product intelligence and unique features can be realized by software which allows to establish strategies against piracy [26].

Based on these findings and the future challenges for mechatronic design in the next chapter a framework for key research areas will be sketched in section 4.4.

4 FUTURE CHALLENGES FOR MECHATRONIC DESIGN

The global megatrends like urbanization, demographic change and sustainability will determine the markets of tomorrow. Urbanization for example leads to challenges for traffic, energy supply and air quality in large cities and agglomerations.

Mechatronics with its ability to integrate different technologies will play a key role to find solutions for these challenges. Mechatronic design has to face challenges in the following 3 main areas: new products, new functions and new methodologies.

4.1 New Products

Sustainability is certainly the most challenging and complex requirement: we learned that the way our modern society consumes energy and materials is not in line with our environment. The efficient use of resources and the concentration on renewable, CO_2-neutral power generation is indispensable to avoid climate change and to assure life on earth. The technological requirement is to enable the change to clean energy generation assuring at the same time the worldwide demand of power for manufacturing, transportation and infrastructure.

Mechatronics can enable solutions which integrate energy generation, energy storage and mobility in an overall concept. Figure 6 shows the increasing integration level of mechatronic systems. Today's cars incorporate already a high level of integration with complex interactions. Driver assistance systems e.g. ESP, brake assist or lane-keeping system integrate sensors and actuators for multiple functions. Further functional and spatial integration is done to reduce costs and to save energy e.g. electric power steering.

The next level of integration is realized by exchanging information between traffic objects. These functions are used to automatically switch from full to dimmed headlights, to avoid collisions or to control traffic management systems.

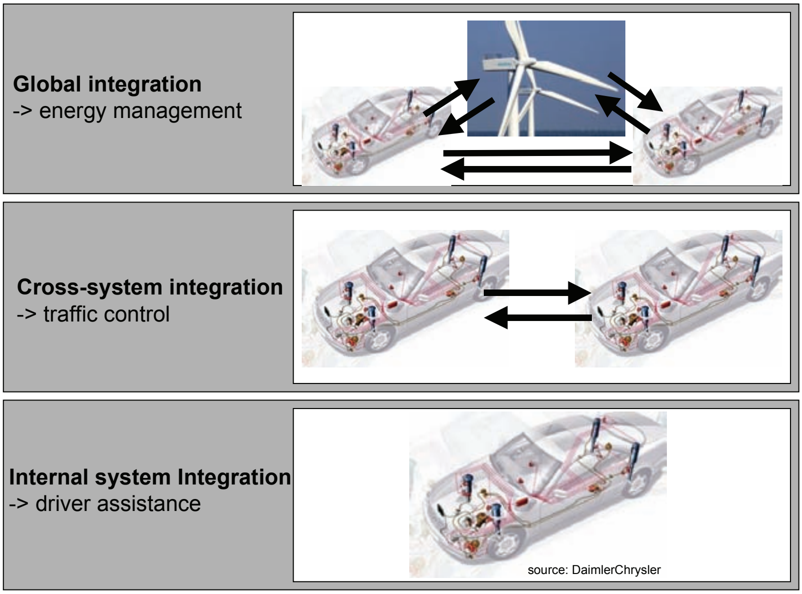

Figure 6. Increasing integration level of mechatronic systems

A global integration level is reached when traffic objects do not only communicate among each other but fulfill multipurpose functions. This is the case for electric cars serving as energy storage. There are worldwide several research activities investigating how electric vehicle mobility can be useful to integrate renewable power generation, amongst others [36]. Renewable energies like wind or solar energy are not base-loadable, i.e. they are not evenly available. This leads to a surplus or an insufficient supply of current at particular times. The "Vehicle to Grid (V2G) technology" could solve this problem. V2G means that electrical vehicles are connected to the public electric current network. They could take current in periods of peak production and supply current into the network in periods of low production.

4.2 New Functions

Mechatronics can also create completely new functions. These are so called smart systems which are able to react to a changing environment (self-optimizing ability) or even react to a unforeseen changing environment (cognitive systems).
An example of a cognitive system is the robot in figure 7. This robot has an internal self-model which can be used to develop new behaviors. In the case of damage of one of its four legs the robot synthesizes a new model of its own topology and learns to move forward with a new locomotive behavior based on the three legs available [37].

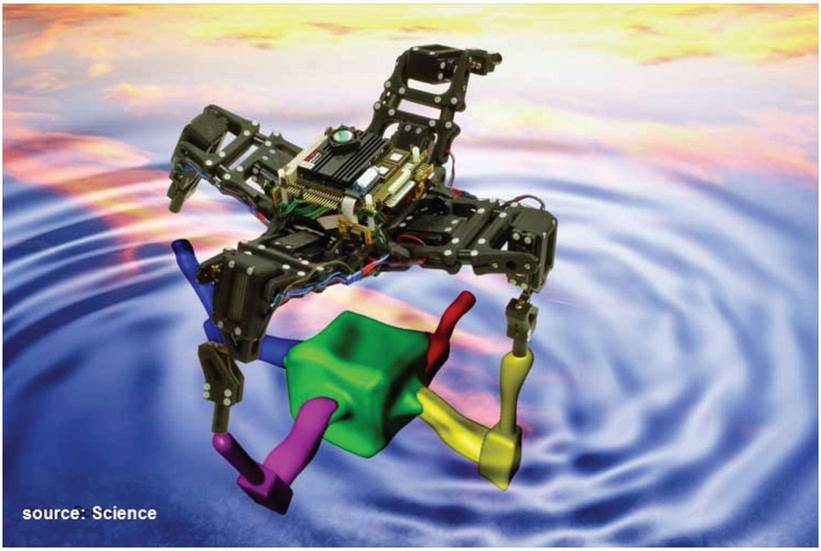

Figure 7. Autonomous Robot with self-replication ability [37]

This is a new function which can help to create more robust products with increasing complexity. With the increasing complexity in mechatronic systems it is more and more difficult to ensure robustness and to anticipate failures. The ability to handle unforeseen failures and to rebuilt system robustness after a damage is a very important requirement.

4.3 New Methodologies

The design of these new products and functions demands appropriate methodologies. They are three main areas to address:
Complexity is the predominant theme. In the very early design phases complexity can be reduced. But with more detailed information and advancing design results complexity is necessary in order to consider all relevant interactions between components and responsible designers. How can interactions be visualized? How can design knowledge be handled and secured (product piracy!)? How can system behavior be validated?

Second area is the overall design specification. With the rising number of design actors (see figure 6) it is more and more difficult to ensure communication between designers. Requirements need to be clear and up to date for everybody, design changes must be transparent through the whole design process and at globally distributed design sites, decisions about solutions should be made on an information base that engineers from different domains can understand. Which level of abstraction is needed for design specification? How can semiformal information be transferred to more detailed design specification in order to simulate systems behavior?
The third area summarizes specific methodologies to consider the requirements for the development of smart systems. A system which can react to changing environment need models for possible environment scenarios, models to specify a system of objectives how to react and a structure model which allows structure adaptations during operation. Cognitive systems additionally need an overall goal model how to lead the system in case of unforeseen situations. How can robustness of design be assured in spite of unknown behavior? How can design models be adapted to changing system behavior? How can the product documentation be assured?

Between December 2007 and January 2008, the mechatronic product development experiences of 140 enterprises have been examined [38]. These enterprises identified the following 6 top challenges of Mechatronic Product Development:

1) Lack of cross-functional knowledge/difficulty to find and hire experienced system engineers
2) Early identification of system level problems
3) Ensuring all design requirements meet the final system
4) Modeling system product behavior until physical prototypes exist
5) Difficulty to implement an integrated product development solution for all disciplines involved
6) Inability to understand the impact a design change will have across disciplines

The 140 enterprises have been categorized according to key criteria into the top 20% of performers (best-in-class), the middle 50% (industry average) and the bottom 30% (laggard) of performers. The best-in-class performers reported the following actions to improve mechatronic design:

Actions	Response
Improve communication and collaboration across disciplines	71%
Increase visibility into status of requirements	49%
Increase ability to predict system behavior prior to testing	46%
Implement or alter new product development processes for a multi-disciplinary approach	43%
Increase real time visibility of product Bill of Materials (BOM) throughout the development process	39%

Figure 8. Top five actions taken to improve Mechatronic Design [38]

4.4 Framework for Key research Areas

The challenges for mechatronic design require methodical support. Future research areas in design methodology can mapped in figure 9. These areas are identified by:
- Findings and shortcomings out of the research review in 3.2
- Impacts from new products and functions (4.1, 4.2, 4.3)
- examination of 140 enterprises (4.3)

Procedure models are needed supporting multi-disciplinarity and coordinating the different disciplines. They should not only support partial phases of conceptual design, but rather the whole design process in an integrative way. Procedure models are needed as well to support the specific requirements of smart systems (goal model, changing system behaviour etc.).
Complexity is a very important issue. Most existing approaches focus on its reduction in order to control. But controlling structural complexity without reduction allows benefits, e.g. customization and barriers against product plagiarism [32]. Ongoing research in complexity analysis is needed.

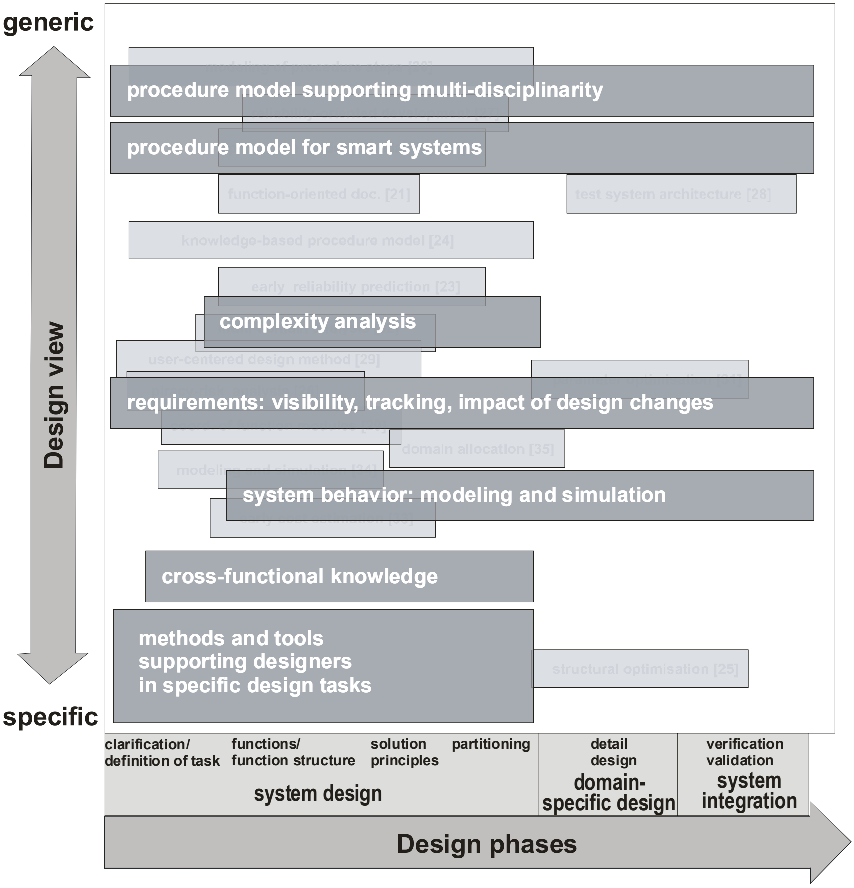

Figure 9. A framework for future research activities in mechatronic design

Requirements are considered to be crucial: they need to be visible at any design stage, changing requirements have to be communicated to all participants in order to check possible design changes.
Modeling and simulation of **system behaviour** has to come along with the conceptual design. The complex interactions need to be analysed for the early beginning.
There is obviously a shortcoming in **cross-functional knowledge** of design engineers. Research could examine how to qualify and train engineers with cross-domain competence and whether knowledge management could support them in design tasks.
In general methods and tools supporting designers in specific design tasks are missing. Research focussed in the past mainly on generic procedure aspects or on partly supporting methods. These specific methods would help to increase industrial acceptance of methodical research because practical benefit could be derived in daily design work.

5 CONCLUDING REMARKS

The potential of mechatronics is huge: Sustainability, urbanization and demographic change demand new technological solutions. Efficient use and renewable generation of power, healthcare and mobility for elderly, safety and security – we find mechatronics in almost any future technical system.
The need to support the designer with appropriate methodologies gets more critical with the increasing complexity.
Potential areas for mechatronic research have been sketched to encourage activities and discussions.

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Contact:
PD Dr.-Ing. Stefan Moehringer
Simon Moehringer Anlagenbau GmbH
Industriestrasse 1
D-97353 Wiesentheid
Germany
Phone: ++49-9383-950-29
Fax: ++49-9383-95015
e-mail: stm@moehringer.com
URL: http://www.moehringer.com