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A RESEARCH FRAMEWORK FOR MECHATRONIC DESIGN

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1. Introduction

Since ICED 2007 the special interest group (SIG) "mechatronics" is discussing research of mechatronic design. At Design 2008 and ICED 2009 several topics and approaches were presented and at ICED 2009 a concentration around certain topics and approaches could be observed. It was decided that the results up to this points should be summarized to a research framework in order to support and give structure to further activities. This paper presents a proposal for such framework and the contents are intended to be discussed in detail at the SIG "mechatronics" session at Design 2010.
A research framework is a structure which allows researchers with different focus and approach to locate their work in a larger picture. It is intended to help such researchers to highlight the specific merit of their research and by this to contribute to an overall advancement of a field of science – in this case the field research of mechatronic design. This paper starts with a definition of the term "mechatronic design" and a differentiation from adjacent fields. A short section underlines the importance of mechatronic design and another short section highlights main future challenges. Afterwards a short summary of the most important research activities is given in order to clarify the state of the art. In section six the core of this paper is presented: the research framework with the subsections research topics (what is worth to be researched), research methodology (how can it be researched) and research road-map (which sequence of research activities may be sensible). The underlying structure which cannot be found in this detailed version in prior publications is the main contribution of this paper.

2. Definition "Mechatronic Design"

In this section firstly a definition of the term "Mechatronics" is sought. What does Mechatronics mean? The opinions what mechatronics are rather blurred: Hewitt [1993] 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. 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 [Kaljas and Reedik 1998]. 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. Mechatronics started to enrich the so far mechanically dominated engineering design at the end of the sixties of the last century. In 1969 the Japanese Ko Kikuchi, president of YASKAWA Electric Corporation, formed the term Mechatronics. This 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 Elec*tronics* (electronics or general electrical engineering) and was protected in the period from 1971 to 1982 as a trade name. 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. Soon the information technology was seen as the third discipline integrated by mechatronics. The next evolution step described "Mechatronics is…the synergetic integration of mechanical engineering with electronic and intelligent computer control in the design and manufacturing of industrial products and processes" [Harashima et al. 1996]. 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. 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 (2000) formulated this definition so broadly that any industrial products and processes can be subsumed under the term of mechatronics. 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.

Consequently in this research framework the definition of Mechatronics as "… the synergetic integration of mechanical engineering, electrical engineering and information technology in the design and manufacturing of any kind of physical industrial products and processes" is proposed.

Also the term "Design" in the sense of "Engineering Design" is extremely difficult to define. A discussion of this term would go beyond the scope of this publication. It is important to note that there is a general agreement that design always focuses on the creation of new entities (usually some kind of product or process) instead of existing entities and that especially engineering design focuses not on the direct creation but on the specification and description of new entities for further production (the result of engineering design is mainly information how a future product should look like (e. g. engineering drawings, block diagrams, lists, etc.) – not the product itself (with the exception of prototypes)). Pragmatically an understanding of design as the process of "creating specifications and descriptions of future products or processes of any kind" is proposed in this publication.

From the clarification of the two terms "Mechatronics" and "Design" a possible definition of the term "Mechatronic Design" can be derived. Based on the considerations listed above "Mechatronic Design" describes the synergetic creation and integration of mechanical engineering, electrical engineering and information technology for the specification and description of any kind of physical products and processes.

2.1 Differentiation from mechatronics

In the first instance Mechatronic Design seems to be very similar to Mechatronics which is a widely researched field with specific conferences, study programmes and even University departments. However, a few important differences can be identified:

- The main focus of Mechatronic Design is on the synthesis of new products and processes whereas the large majority of publications, methods and tools of Mechatronics is focused on the analysis of such products and processes.
- In Mechatronic Design the important role of creativity and uncertainty existing in any design process is addressed; in contrast such points are frequently not the object of discussion in Mechatronics.
- In Mechatronic Design as in other branches of Design Science the human designer, his/her thinking and his/her behaviour is included into the investigations and reported insights; in Mechatronics frequently a very impersonal argumentation style is employed.
- The early phases with extremely abstract and immature descriptions of the product or process under development are included in the research work into Mechatronic Design; the point of main emphasis of Mechatronics is usually on the later phases.

- As a consequence of the inclusion of early phases in Mechatronic Design also very abstract product and process models need to be investigated and generated; in general Mechatronics this kind of model is usually not the main point of interest.

2.2 Differentiation from conventional design

Many design researchers argue that Mechatronic Design is not much different from conventional engineering design (the term "conventional" is used to describe the design research which is not focused on mechatronic products and processes – no negative bias of any kind is intended). Most products these days contain elements of mechanical engineering, electrical engineering and information technology – therefore any design could be understood as mechatronic design. For a discussion of this viewpoint two important facts have to be considered. Firstly it has to be clarified that the sole existence of elements of mechanical engineering, electrical engineering and information technology does not lead to a high-level mechatronic product. It is important to distinguish the different levels of mechatronic products. One possibility to make this distinction was proposed by Stetter&Pulm [2009] on the basis of systems theory (compare Pulm [2005] - Figure 1).

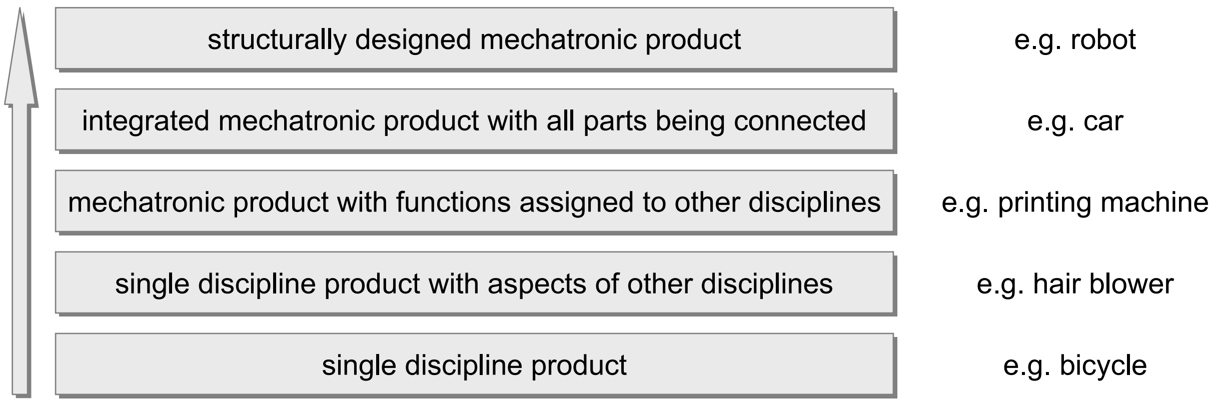

Figure 1. Different Levels of Mechatronic Products

The design of a single discipline product with aspects of other disciplines might be very similar to conventional design; in contrast the design process of a structurally designed mechatronic product has to be different from conventional design as an integral mechatronic structure has to be achieved. This leads to the second important fact that distinguishes mechatronic design form conventional design. The second important fact is that the design of mechatronic products is different from "conventional design" in many aspects:

- The complexity of mechatronic products differs from conventional products in terms of quantity and quality. Mechatronic products are often characterised by a large number of different components which leads to increased complexity. Additionally, the interaction between these components can be much more intensive than in conventional products. This fact results in a greatly increased complexity which might be the key challenge in mechatronic design.
- Mechatronic products usually combine many physical phenomena in order to achieve the desired functions. The higher level of multi-physics in mechatronic design presents another key challenge.
- The engineers in the development of mechatronic products usually do not share a common education background. This leads to the fact that no common models (mental, graphical and physical) are readily available. Additionally, these engineers do not employ a common nomenclature.
- Even the engineering philosophies in mechatronic design differ. Engineers educated in mechanical engineering usually apply a safe-life strategy: they try to design their product so strong and so stiff that they will not fail during their lifetime under normal conditions. The central approach especially in information technology is very often different: the application

of a fail-safe paradigm leads to products which may fail but this failure will not lead to serious consequences. In mechatronic design these two philosophies have to be combined in order to achieve products which fulfil the requirements regarding safety, reliability and economy.

2.3 Differentiation from systems engineering

Mechatronic Design usually is focused an the creation of specifications and descriptions of complex products and processes. For the development of complex systems usually the strategies, methods and techniques of systems engineering are proposed. Systems engineering is commonly defined as a general applicable guideline for the development of complex systems so that these systems can fulfil the technical and societal requirements in a integrative, holistic manner. In this instance no major difference to Mechatronic Design can be found. The main difference lays in the focus: systems engineering is focused on organisational aspects and technical aspects which are usually more abstract then physical phenomena. Mechatronic design on the contrary concentrates on the technical content and explicitly includes the physical phenomena of the products and processes under development. In recent years the term "Mechatronics Engineering" was proposed as a combination of these two adjacent and overlapping fields of interest (or methodologies).

3. Importance of Mechatronic Design

In the last section a definition for Mechatronic Design was sought and the difference to other important concepts was elucidated. This section aims at underlining the importance of Mechatronic Design and by this the importance of research of Mechatronic Design. There can be no denying the fact that the share of mechatronic components and function in the products of the consumer market as well as the professional markets has been increased enormously over the last two decades and will further increase. Additionally, many functions of current products (e. g. diagnostic functions in cars starting from the detection of defective light bulbs and reaching into plausibility checks of the stability system of a car) can only by realised by means of the integration of mechanical engineering, electrical engineering and information technology. However, many authors [e. g. Stetter&Pulm 2009] point out that in industrial practice still organizational and personal boundaries hinder this integration. The development are still nearly independent activities of different persons and different departments. The communication, integration and synchronization is sought by means of more or less frequent meetings, phone calls and e-mail traffic. Even more important, in many companies still no cross-disciplinary concept phase can be identified. In general, a large gap between the overwhelming chances and demands connected with Mechatronic Design and the applied strategies, methods and tools can be observed.

4. 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 three main areas: new products, new functions and new methodologies.

4.1 New products

Sustainability is certainly the most challenging and complex requirement: there can be no denying the fact that the way our modern society consumes energy and materials is not in line with the 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. It presents one main technological requirement to enable the change to clean energy generation assuring at the same time the worldwide demand of power for manufacturing, transportation and infrastructure. Mechatronic design can enable solutions which integrate energy generation, energy storage and mobility in an overall concept. Today's cars incorporate already a high level of integration with complex interactions. Driver assistance systems e. g. ESP, brake assistance or lane-keeping systems 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 may be 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. A global integration level is reached when traffic objects do not only communicate among each other but fulfil multipurpose functions. This is the case for electric cars serving as energy storage. Worldwide several research activities can be identified investigating how electric vehicle mobility can be useful to integrate renewable power generation, amongst others. 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

Mechatronic design 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 may be self-optimizing robots. Such robots have an internal self-model which can be used to develop new behaviours. In the case of damage of one of its legs a robot of this kind synthesizes a new model of its own topology and learns to move forward with a new locomotive behaviour based on the legs still available. 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 behaviour be validated?

The second main area is the overall design specification. With a rising number of design actors 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 semi-formal information be transferred to more detailed design specification in order to simulate systems behaviour?

The third main area summarizes specific methodologies to consider the requirements for the development of smart systems. A system which can react to changing environment needs 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 in order to lead the system in case of unforeseen situations. How can robustness of design be assured in spite of unknown behaviour? How can design models be adapted to changing system behaviour? How can the product documentation be assured?

5. Important Research Activities

A detailed description of key research activities in mechatronic design was compiled by Möhringer [2004] and updated [2009]. 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. The first key topic to deal with complexity can be 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 [Diehl et al. 2008]. The use of UML diagrams to represent structural and behaviour models of mechatronic systems may as well be helpful [Johar and Stetter 2008]. The 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 modelling approach can support the partitioning [Jansen and Welp 2007]. Design iterations are necessary in order to find the overall optimum, but are time-consuming and cost-intensive as well. A classification of iterations and an approach on the control may help to avoid unnecessary iterations. Design automation is the second 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 [e.g. Campbell 2007]. The 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 behaviour. The behaviour 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, behaviour and shape [e.g. Paetzold and Schmid 2008].

6. Research Framework

This section is the culmination of this paper – the presentation of a proposed research framework for mechatronic design. As underlined before, this framework is the result of discussions at three earlier SIG mechatronics sessions and is intended to be intensively discussed at Design 2010. Firstly, it will be discussed what is worth to be researched. Secondly, it is investigated how it can it be researched. Finally, first insights which sequence of research activities may be sensible are summarized. These points are then summarized in the proposed framework for research of mechatronic design (Figure 2).

6.1 Research topics

As stated before, *complexity* is a very important issue – mainly the main challenge of Mechatronic Design. Most existing approaches focus on its reduction in order to allow the surveillance and control of development processes of mechatronic products. But controlling structural complexity without reduction allows benefits, e. g. customization and barriers against product plagiarism. Ongoing and further research in the direction of complexity analysis and complexity management is strongly encouraged.

Stetter and Pulm [2009] report that in successful mechatronic product development processes in industrial practice usually a high amount of chaos is visible. The discussion at ICED 2009 led to the hypothesis that a certain degree of chaos might be advantageous for Mechatronic Design as other complex systems such as the market economy also allow a considerable degree of chaos. Obviously Mechatronic Design still requires some control such as clear objectives, documentation of decisions as well as the process, synchronization of different activities and integration of components, functions, organisations and people. The task to determine the right *balance between chaos and control* and the investigations of possible means to achieve this balance is a promising field for further research.

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 also needed in order to support the specific requirements of smart systems (goal model, changing system behaviour etc.).

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. Research into *requirement management* is therefore another promising field

Modelling and simulation of system behaviours are key elements towards effective and efficient processes but have to start already in the abstract conceptual design phases. The complex interactions need to be analysed from the early beginnings of Mechatronic Design – this requires novel approaches and tools. Especially for this topic also case studies (success stories) are helpful for dispersing knowledge and experiences throughout the community.

In contrast to the procedures usually taught in engineering science many mechatronic product development processes in academia and industrial practice are characterised by the frequent presence of trial-and-error procedures. This very popular iterative procedure is obviously very often applied successfully and could be labelled "*prototyping*". Especially in Mechatronic Design this procedure also aids communication as physical prototypes are usually easier to understand than abstract product models. Design research is describing the basic structure of such procedure schemes in the problem-solving-cycle. However, concrete recommendations and tools for prototyping are still missing and can be the topic of further research work.

The general trend towards products and processes with larger complexity and an increased number of versions and variants can be easily observed. This will lead an increasing amount of design work. The design of complex computer systems is already today only possible if *design automation* techniques such as automated layout are applied. Such techniques are also necessary for Mechatronic design. However, due to the specific nature of Mechatronic Design this transfer and adaptation will be everything but easy.

Mechatronic products and processes offer numerous possibilities to include conventional and advanced *diagnosis and control* techniques. Already today an abundance of sensory information is available in products and processes or could be easily and cheaply be made accessible. Therefore a strong advancement of such techniques can be expected in the next decade. From this level the next probable steps will lead to *self-optimizing/cognitive systems*. The foundations for this step will be laid in today's research.

There is obviously a shortcoming in cross-functional knowledge and capabilities of design engineers. Research concerning *mechatronic education* could examine means to qualify and train engineers with cross-domain competence and whether knowledge management could support these engineers in their 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. In order to clarify the ultimate goal of further research topics it is proposed to clearly distinguish between research that intends to expands human knowledge and research that intends to directly help design engineers in Mechatronic Design practice and education. A finer distinction is included in the framework in Figure 2.

6.2 Research methodology

At the plenary sessions of past conferences such as ICED, Design ASME DTM or TMCE it was frequently pointed out that many scientific papers in the scope of design science do not state the research methodology. However, such statement is inevitable in order to allow the critical reader to assess the validity, scope and applicability of the research result. Additionally it is important to note that rigorous requirements concerning the structure of publications will not suit the inhomogeneous, open and ever changing field of design. Many important research works in this field do not follow the classical hypothesis-experiment-evaluation scheme. Very often the need for some methods and tools is well established at the start of a new research project and the development of these methods and tools are research tasks by themselves and logical deduction may be an extremely valuable research method. Furthermore, some strategies, methods and tools are too advanced (in the sense of too different from industrial practice) to be sensibly tested in industrial practice in the scope of one research project. Still, it is necessary that readers know such limitations in order to be able to value the research results. A description of the research method must be part of any Mechatronic Research and has to openly discuss such limitations.

6.3 Research road-map

The headline "research road-map" may evoke the expectation that the authors will be able to present a sensible road-map for research of Mechatronic Design for the next decade. This is unfortunately not the case. The start of a common research road-map is intended to be discussed at the Mechatronic Design SIG session at the Design 2010 conference. In this paper the authors only want to highlight some important criteria to develop and sort this road-map. The following points are consequently meant as a preparation of the workshop:

- Urgency: the main criterion for selecting the next research topics is their importance in industrial practice. The community has to seek the assessment of engineer and managers in industry in order to develop a research road-map.
- Chances for quick wins: the acceptance and financial funding of research projects is very often bound to tangible results which can be achieved quickly. Therefore, the possibility to achieve such quick wins should also be assessed.
- Solvability: it is inevitable for the development of a research road-map to assess the time and expenditure needed to develop tangible and useful results concerning a certain research question.
- Scope: science has the general task to answer questions around human existence. Therefore, it is not sensible if all design researcher concentrate on one kind of Mechatronic Design product and process, because in this case no holistic knowledge can be developed in the community. Similar to a product portfolio of a company with different products a research portfolio could be used in order to identify areas needing research. Three such portfolios are proposed in the framework (Figure 2).

6.4 Framework

In the discussion in the three prior sections the main contents of a research framework for mechatronic design were developed. It was attempted to clarify *what* is worth to be researched (core issues and research objectives), *how* it can be researched (research methodology) and *which* sensible *descriptions of the scope* of the research are useful. These contents are summarized in Figure 2:

- a short list of important research questions – the ten core issues,
- a distinction of general research objectives intended to clarify the ultimate goal of a research project,
- a distinction of research methodologies which aims at allowing the reader to evaluate the validity, firmness and scope of the research results and
- three portfolios allowing to investigate the scope of a research project and to identified fields that were not addressed yet.

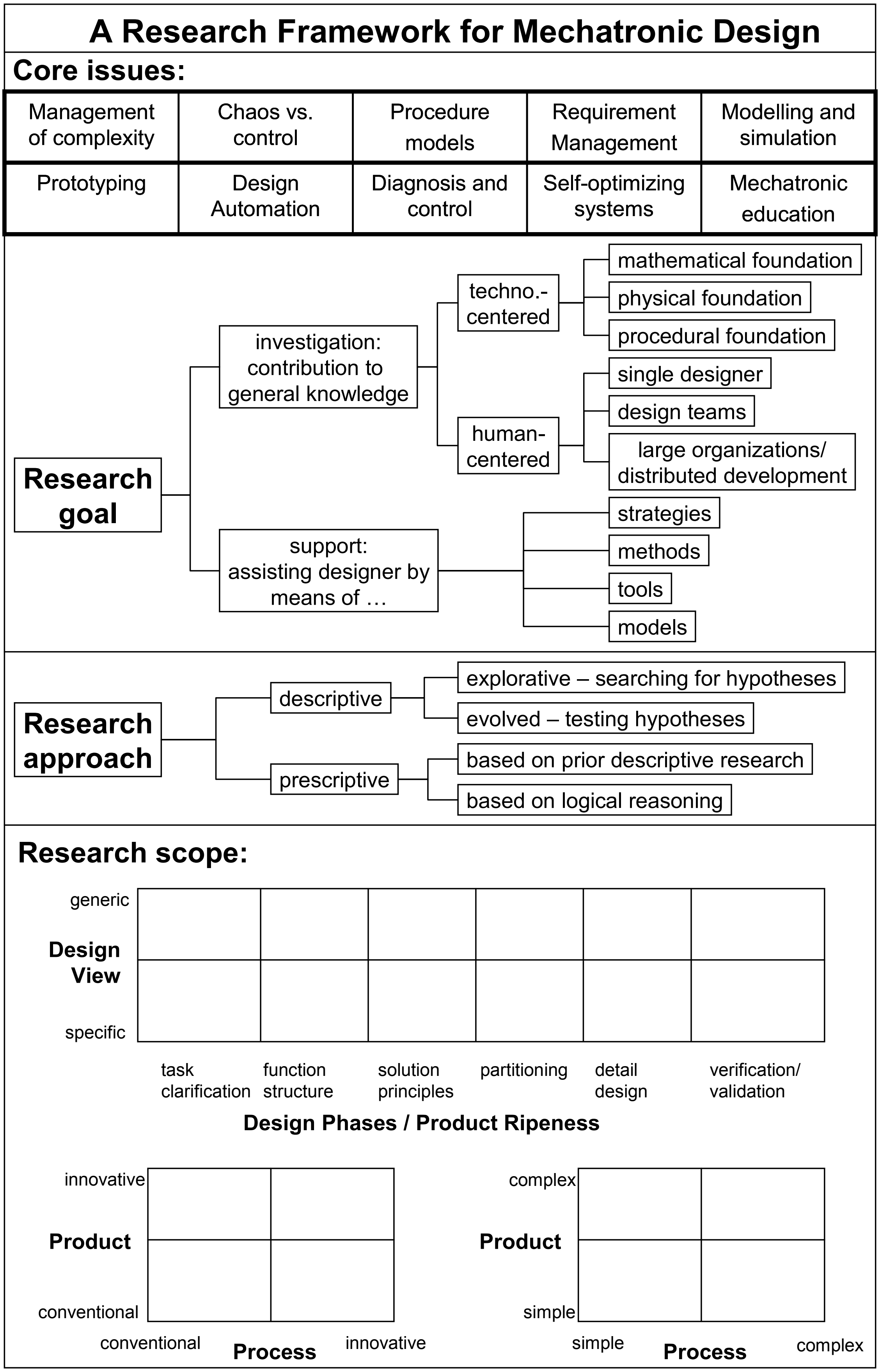

Figure 2. Research Framework

7. Summary

This paper is mainly intended as a basis for the discussion in the special interest group (SIG) "mechatronic design" at the Design conference 2010. Ten promising core issues for further research of Mechatronic Design were identified in research work and prior discussions in sessions of this SIG and form the core of the framework. Additional parts of the framework are aimed at the clarification of research objectives and methodologies and at the common development of holistic knowledge about Mechatronic Design in the research community. It is intended to develop a road-map for research into "mechatronic design" at the SIG session at the Design conference 2010; as a basis for this endeavour criteria for developing and sorting this road-map were introduced.

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