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METHODOLOGY FOR THE DEVELOPMENT OF MICRO-ELECTRO-MECHANICAL-SYSTEMS

Robert Watty and Hansgeorg Binz
Institute for Engineering Design and Industrial Design (IKTD), Universität Stuttgart, Germany

ABSTRACT
MEMS technology allows the significant miniaturisation and integration of products based on diverse micro technologies. A world without this technology is nowadays hard to imagine, although they are often not visible and just a vital part of technical systems, e. g. automotive, medical or household products.
In particular, the high interdisciplinarity and the very technology-driven development challenge both knowledge and cooperation skills of MEMS designers from sometimes very different domains. Structured development processes for this complex task are not common practice up to now due to the novelty of MEMS technology, although appropriate methodologies have been successfully established in many other disciplines.
This paper summarises requirements to a methodology for the development of MEMS products, suggests a new and detailed development process supported by MEMS-specific methods and describes the evaluation of process and methods in MEMS development projects.

Keywords: MEMS, Development Process, Methodology

1 INTRODUCTION
Right from the beginning, a few decades ago, MEMS (Micro-Electro-Mechanical-Systems) technology was regarded as a worldwide key technology with enormous potential for the 21st century. The market for MEMS has grown around 20 % per year over the last decade and MEMS products are meanwhile used in various fields, e. g. in the automation, automotive or bio-medical sector, to enhance conventional applications or to open new areas of technology [1]. MST (Micro-Systems-Technology) allows the production of such systems with extreme mechanical precision and high repetition accuracy.
The placement of new innovative products on these markets requires a large investment in research and development as well as a systematic organisation of both product development and production chain to accelerate the process from the start of development to the market introduction of MEMS.
Therefore, it is important to master the actual challenges for the industry: the trend towards globalisation, growing complexity of both products and processes, the need for knowledge and experience management, increasing commercial pressures and the request for sustainable products.
Up to now structured development processes for MEMS are not common practice due to the novelty of products and manufacturing technologies. Only a few systematic procedures are known [2] but not established and the exchange of knowledge of development proceedings is limited.
The suggested approaches, which until now are often derived from the development of microelectronic products, use microelectronic description instruments and design methods. They are often based on the partition of the system into components that are more or less parallelly and separately developed or taken from databases and finally integrated into a new microsystem. The fundamental problem of these approaches is the reuse and combination of still existing solutions. Creative aspects like the search for new concepts of the entire system or its parts are not explicitly demanded. The mostly automated design processes for microelectronics lack the consideration of intuitive and heuristic design steps required for MEMS. This results in a delayed consideration of disturbing influences and integration aspects that are essential for the design of MEMS. Up to now the known approaches are, therefore, immature and require enhancements [4].

MEMS products are currently often based on brilliant ideas without a systematic approach. Continuous improvement to support a shorter development time is often not applied sufficiently. Experience in other disciplines, e. g. mechanical, electrical or software engineering, has shown that a well structured development process allows the exploitation of the wide possibilities of MEMS, the organization of knowledge for further developments and the development of marketable products with a high reliability. Established development procedures in these disciplines are appropriate to consider their adaption to the specific requirements of MEMS design.

2 REQUIREMENTS TO A DESIGN METHODOLOGY FOR MEMS

Conditions in MEMS technology differ significantly from other domains. MEMS technology deals with the integration of diverse micro technologies in complex and highly integrated systems under continuously developing boundary conditions. Successful development of MEMS demands a customised and rapid development process and requires attention to their special characteristics: essential cooperation of experts of various fields, a wide range of manufacturing technologies and technology-driven development. A suitable development process must fulfil several requirements, Figure 1.

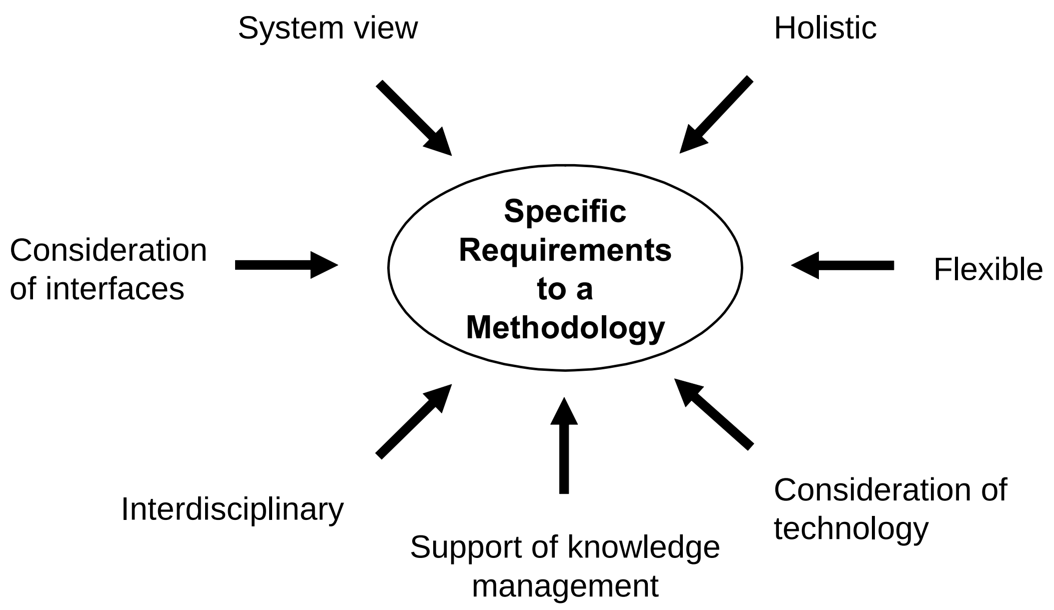


Figure 1. Requirements to a methodology

The significant and interdisciplinary miniaturisation and integration of MEMS allow new technical principles and properties but also increasingly lead to the limits of manufacturing technology. Furthermore, it causes influences between MEMS components and results in disturbing physical effects of miniaturisation. For example, electromagnetic effects allow electrostatic micromotors but also cause lubrication problems or deflection [3]. MEMS require not only efficient components but also their correct and reliable interaction to fulfil the function of the entire system. The essential multidisciplinarity of MEMS design and the effects of miniaturisation demand a common view on process and product [4], [5]. A system view on MEMS is also important to ensure the proper function of the system. Keeping the whole system in mind also supports interdisciplinary teamwork and helps to consider interfaces. An appropriate integration of interfaces and components of the total system is also important, because MEMS are usually unfixable and mostly used in substantial functions of surrounding systems [2].

Interdisciplinary teamwork and the coordination of experts from different fields, e. g. micromechanics, microfluidics or microbiology, are fundamental in MEMS design [6]. The diversity and the continuous modification of technologies, materials and applications challenge the designers of various fields. Interrelations, a wide range of manufacturing technology and a close interdependence between products and production technologies can cause failures due to insufficient coordination between the domains.

A good understanding of physical and technological background and a comprehensive and holistic approach is, therefore, essential for the development of suitable and long-term successful products.

Storing knowledge and providing it purposeful is a vital precondition for the development of high quality MEMS products. This requires management of interdisciplinary and continuously advancing knowledge, e. g. by means of design catalogues [7].
The manufacturing technology plays a major role in MEMS development. MEMS designers have much more questions concerning manufacturing than macro designers [4], because manufacturing technologies are often immature and continuously developing. Product development and technology adaptation are often carried out at the same time. The close connection between the development of product and manufacturing process leads to a technology-driven development process unlike common development procedures in other domains. The development of MEMS requires a close teamwork between experts and constantly up-to-date knowledge to utilise the potentials of MEMS and their manufacturing technologies [6]. Simultaneous development of product and manufacturing process requires attention during the development process and knowledge management supported by adequate methods [4], [8].
The complexity and broad variety of MEMS technology makes it difficult to provide a standard procedure for MEMS design. The approach must be more universal than known development processes in the disciplines involved, but at the same time closely connected to the design of single systems [9]. This requires an adaptation of the methodology to specific design tasks.
Many disciplines use approved development methodologies for product development. Examples are the VDI-guidelines for mechanics [10] and mechatronics [11] or widely automated design procedures in microelectronics [12]. These methodologies are generally constricted to certain disciplines and do not sufficiently include the interdisciplinarity and particularly the attention to system interrelations demanded for the development of MEMS. Manufacturing aspects usually play a minor role in product development than in MEMS technology, because the demanded technologies are usually more mature in most other disciplines. Thus requirements to a MEMS-specific design process are not fulfilled by processes of other disciplines.
That is why a simple transfer of an existing methodology to MEMS design is not possible. The following introduces a newly developed approach for the design of MEMS based on the procedure described in VDI 2206 [11].

3 METHODOLOGY FOR THE DEVELOPMENT OF MEMS PRODUCTS

3.1 Design procedure

Figure 2 shows the suggested V-Model describing the general development process for the development of MEMS products [13].

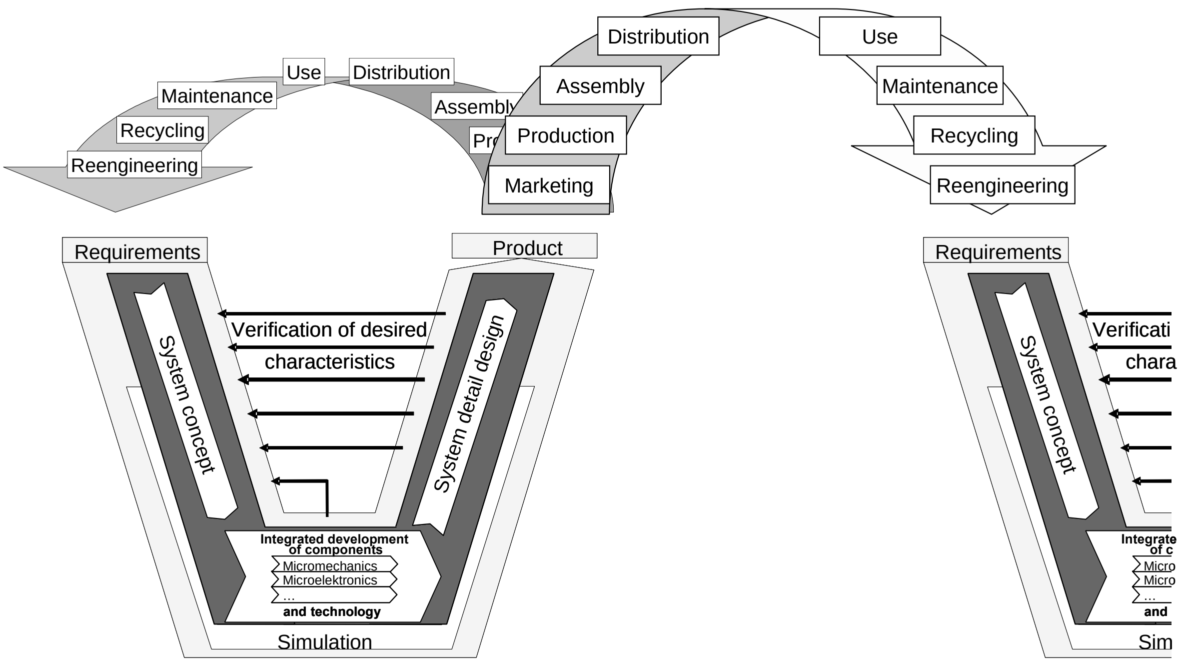


Figure 2: Suggested MEMS development process

The development process starts with the generation of an interdisciplinary system concept based on the desired requirements. It is continued by the most important part of MEMS development that differs significantly from other domains: a parallel development of the systems components in diverse domains and the manufacturing technology. A proper development procedure in this phase is fundamental to avoid parasitic interactions between the elements of the system and its environment and is essential for a working and manufacturable system. Procedures for the development of subsystems in different domains can differ but demand a close teamwork of the domain experts, permanent consultations and the use of adequate methods for the integration of the system [6] as well as concurrent engineering.

The concluding system detail design phase includes the further integration of components with a focus on the revision of the system and the verification of the desired characteristics of the product.

The development process is embedded in the product lifecycle to incorporate knowledge and demands from different stages of the product's life. This may include smaller revisions within a development cycle or severe differences, e. g. in function, with the development of a practically new product. Simulation as early as possible helps to predict the properties of the system and supports both integration and supply of efficient technology.

The development of domain-integrated simulation tools is in progress but up to now not satisfactory.

The consideration of parasitic influences and the simulation of the system and its components at an early stage is one way of forecasting properties and preventing iterations. Therefore, the complete development process from the creation of the system concept to its detail design should be accompanied and verified by simulation and gauging. Continuous improvement supports the detection of functional failures and their elimination at an early stage of the development process. The use of models and their simulation in a computer is in the meantime a tool that is used in many areas of technology. Simulation tools are also a long-used and central part of MEMS development [15].

MEMS development is characterised by the necessary involvement of different domains in a simulation that requires not only the modelling of single components but also their integration into a general view [16]. This demands diverse levels of abstraction and description as well as the consideration of e. g. temperature distribution or disturbing electromagnetic fields [15].

Mechanical theories and calculations are basically applicable, but the micro world requires the consideration of its particular characteristics. The close relation between design and function, the mechanical properties of the basic materials, the utilisation of multi-layers, stresses resulting from assembly processes or strong interactions between mechanical and other, e. g. electrical or magnetic, fields must be regarded in the simulation of MEMS [15]. Therefore, MEMS simulation demands tools that are able to cope with heterogeneous and complex systems [17].

The described general process must be adapted and more precisely specified for the demands of specific product developments.

The first step of the development process is the generation of the system concept, Figure 3. This requires a fundamental planning of the development based upon a systematic and interdisciplinary clarification of the task far beyond purely functional aspects. The tapping of the full potentials of MEMS technology requires to centre the MEMS solution from the beginning instead of minimizing conventional products. Thus the system´s task and environment must be accurately analysed. An abstract view on the problem avoids predetermined solutions and supports the integration of the system.

Even in the conceptual phase, MEMS design is strongly influenced by the interdisciplinarity of products and the immaturity and diversity of manufacturing technologies. If the manufacturing technologies are not specified by existing equipment, they often have to be advanced parallelly to the product and, therefore, should be selected as early as possible and continuously considered during the development process. Requirements of the participating disciplines and their interaction must be regarded to avoid disturbing interactions of MEMS components and undesirable physical effects of miniaturisation.

A well balanced system concept supports the interdisciplinary and integrated development of the components, Figure 4.

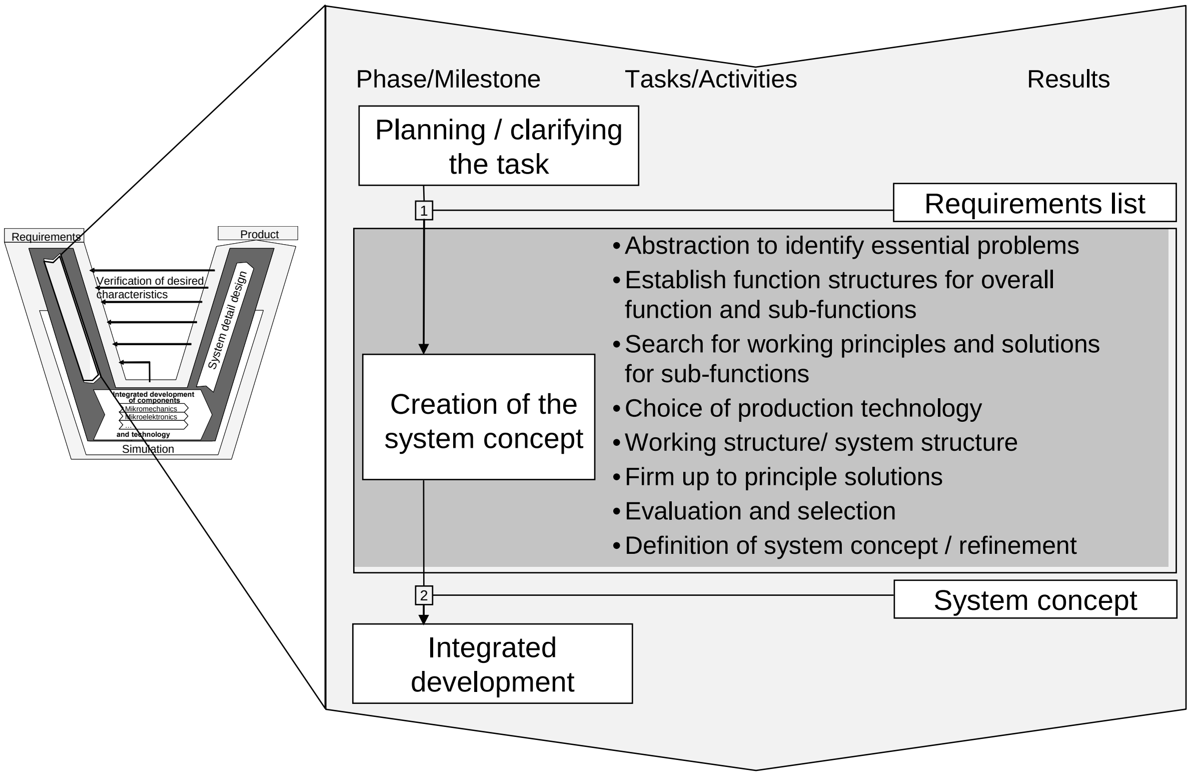


Figure 3. Subtasks of the system concept generation

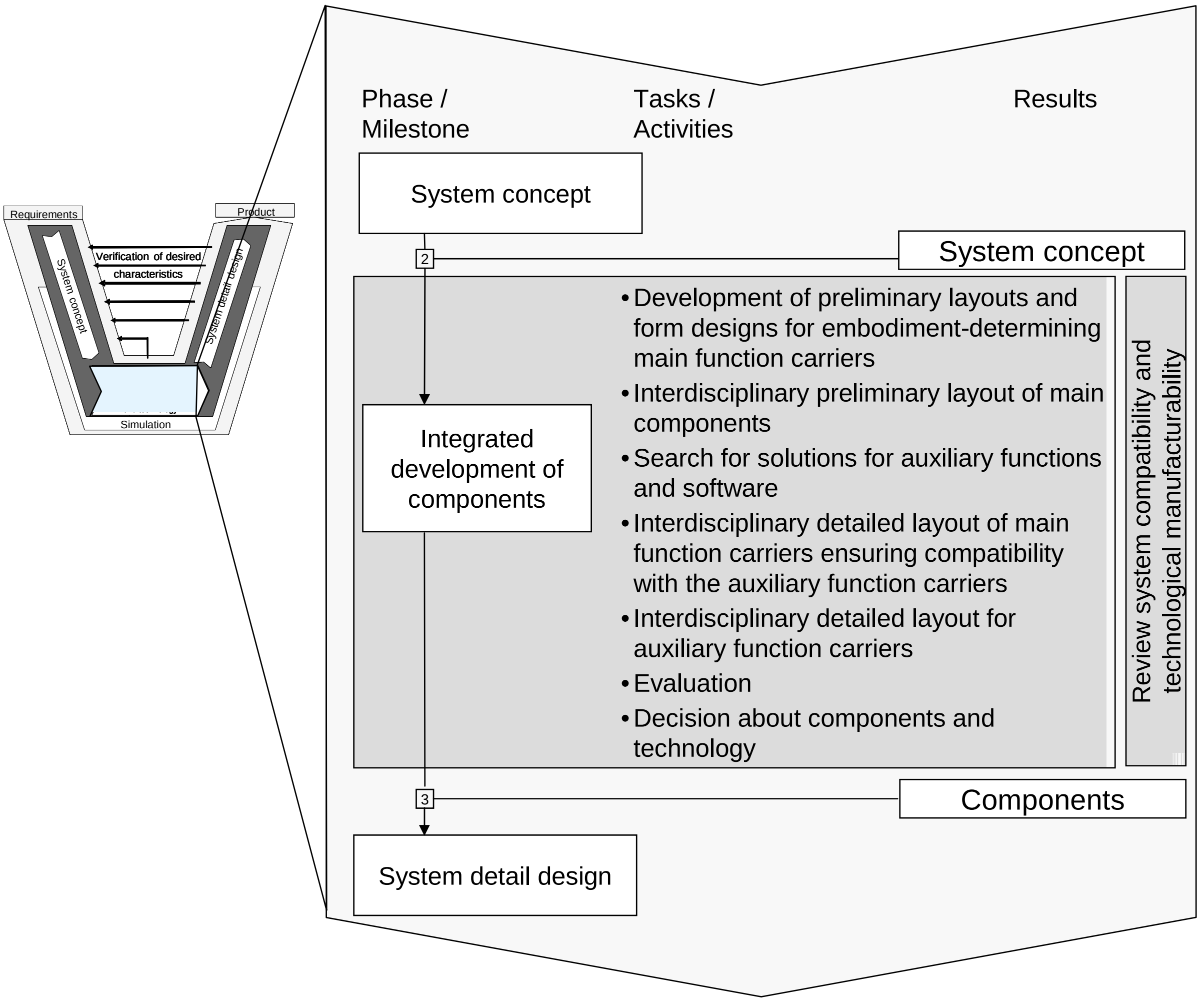


Figure 4. Subtasks of the integrated development of components

The necessary steps are similar to the procedure in mechanical engineering [14], but consequently extended to the specific needs of MEMS design. Subtasks have to consider interdisciplinary aspects and to integrate design procedures of the involved domains, e. g. microelectronics or microoptics. System compatibility and manufacturability have to be reviewed simultaneously during the development process.

The integrated development of components results in a widely adjusted system. The following system detail design, Figure 5, aims at a final consolidation and verification of the system.

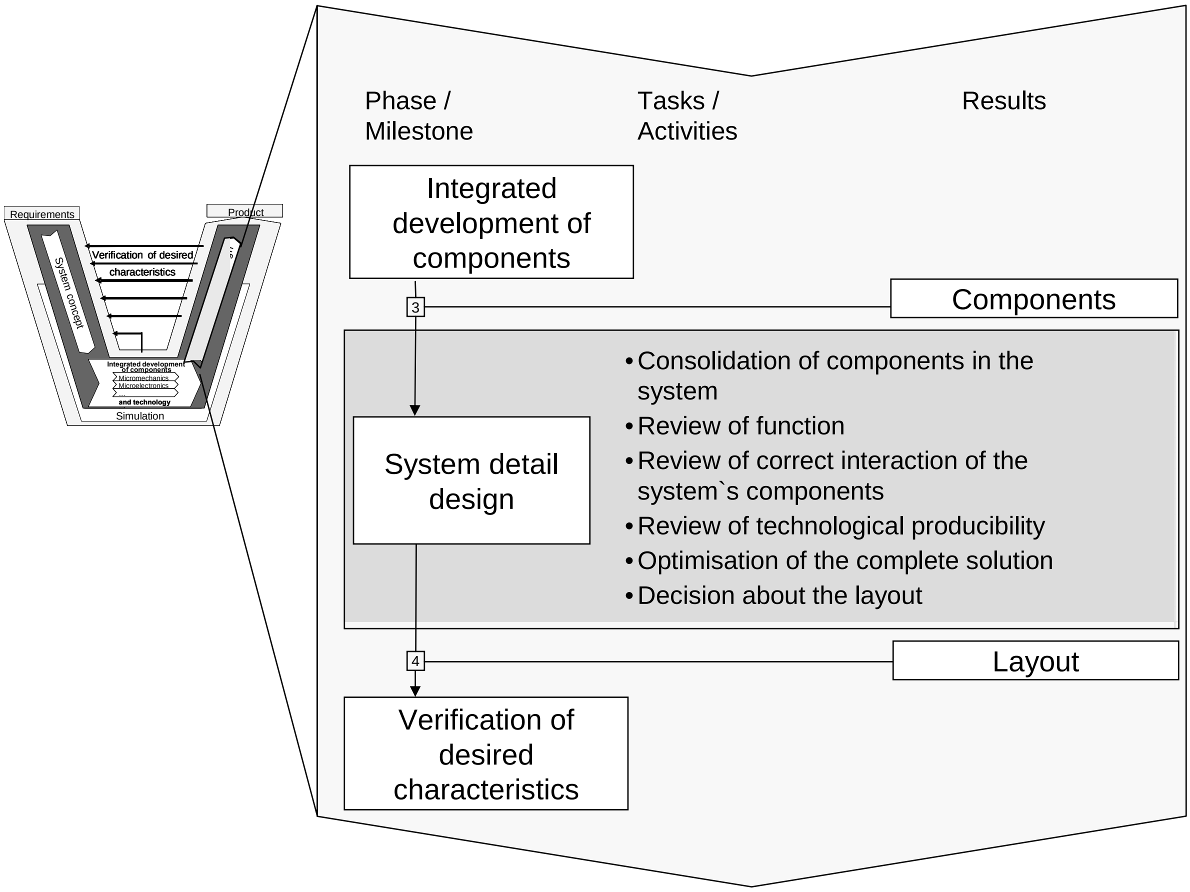


Figure 5. Subtasks of the system detail design

This requires an intensive review of the function of the system, particularly the correct interaction of the components. The designer must finally verify assumptions about parasitics and consider unwanted as well as desired influences inside the system in order to optimise it. The manufacturability of the complete system must be checked and coordinated with the production equipment. The result of this phase is a detailed layout of the desired product. The final decision about the layout is followed by testing procedures to verify the desired characteristics of the system and to compare them to the requirements list.

A well-defined and continuous MEMS development process like the classic process for mechanical tasks is often not possible. It is disturbed by the fast-changing environment and the simultaneous development of the manufacturing technology. Therefore, the development process is characterised by iterations, Figure 6.

Starting with the planning of the product, the basic V-model is continuously repeated with results in a higher stage of maturity and concretion from very basic demonstrators to the final product. The reliability and function of intermediate results must be validated, compared to the requirements list and the manufacturing technology, before a more mature version of the product is developed. The final objective at the end of the iteration process is a product that fulfils all functional, economic and technological requirements.

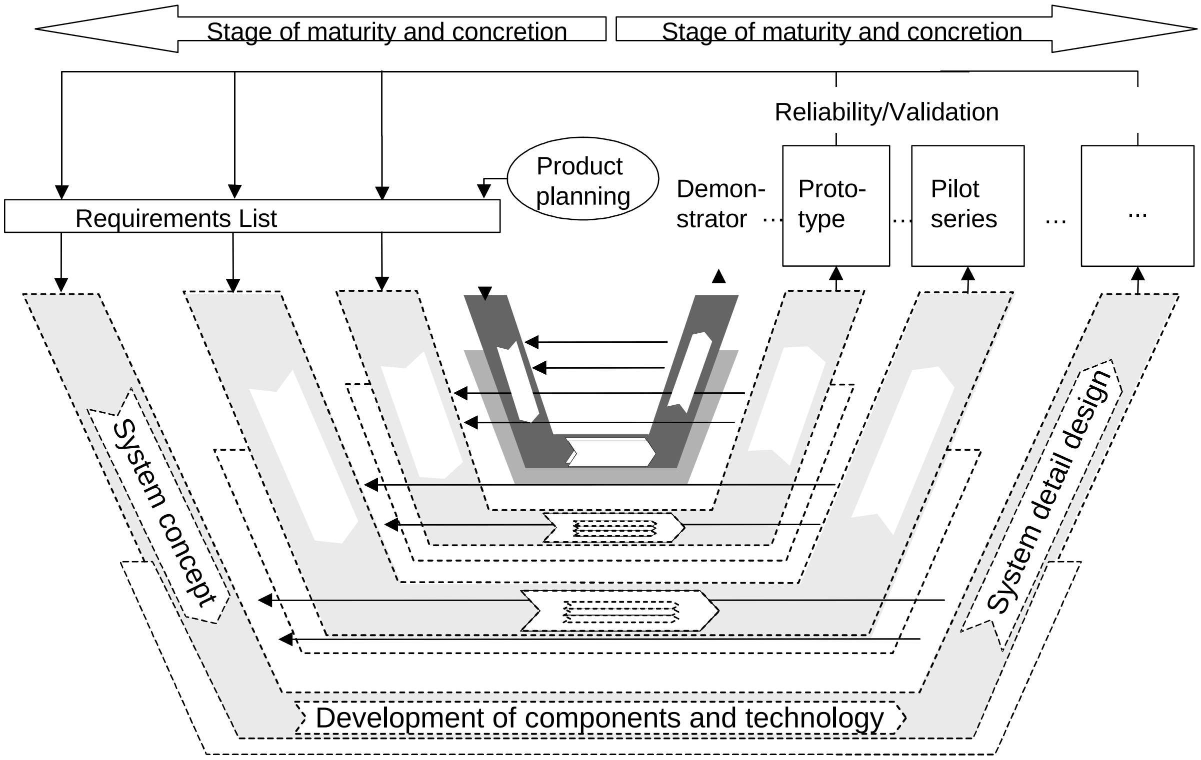


Figure 6: Iterations in the development process

3.2 Integration into organisational context

The development of new products always happens in the organisational context of a certain business environment, Figure 7.

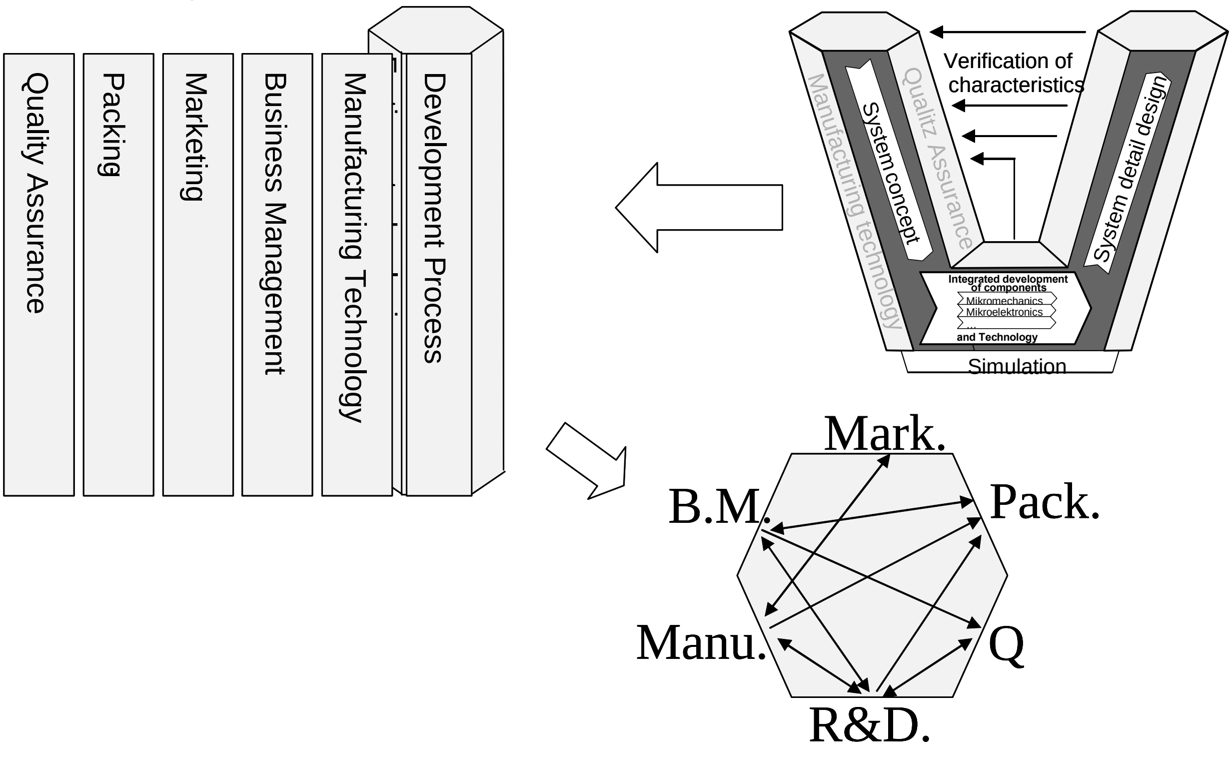


Figure 7: Support of different views on MEMS design

This requires the cooperation of technical and non-technical departments, mutual understanding and accurate communication. It leads to a three-dimensional consideration of the originally two-dimensional V-model to support different views on the development process. Designers have to consider e. g. manufacturing, quality and packaging aspects, but also economic and marketing factors. Their two-way interrelations and dependencies become visible if they are arranged on the surfaces of a polygen-based volume. These relations should be regarded during the development process as described in [6].

3.3 Supporting methods

The MEMS development process can be supported by many methods used in other disciplines, Figure 8. Moreover, methods are useful in the potential weak points of MEMS design: The collection and preparation of knowledge in continuously developing conditions and the handling of internal and external interactions of the system's components and its surroundings.

- Checklist for main characteristics for the requirements list
- Matrix for the selection of materials
- Matrix for the selection of technologies
- Catalogue of physical effects
- Working structure for the recognition of interrelations
- Classification schemes/ Design catalogues
- Guidelines for embodiment design
- System-FMEA

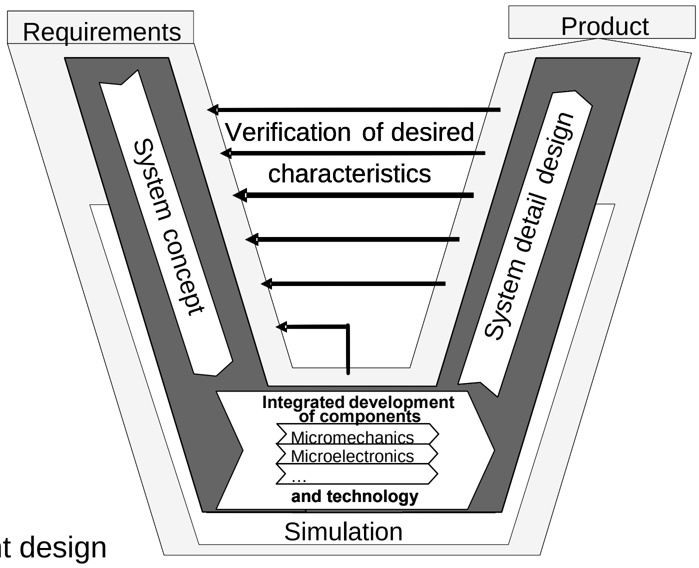


Figure 8: Methods in MEMS Design (selection)

The examination of the entire system and the consideration of aspects of system integration can be achieved through the use of a newly developed working structure and a corresponding Design Structure Matrices (DSM) [6]. Both methods clarify the dependencies between the components of the system and enable the designer to regard all influences and to be sure to gather all information from diverse domains influencing the design process.

Knowledge management can be solved by systematic supply of information about physical effects, design catalogues and regularly updated guidelines about geometry, manufacturing limits and materials, Figure 9.

Actual data sheets are particularly important because of the technology-driven development of MEMS. They can provide design rules for different technologies and support an effective and actual repertory of limits of the manufacturing technology. The fast technological advancements demand a continuous review and change of design rules, preferably computer-based.

Institut für Konstruktionstechnik
und Technisches Design
Universität Stuttgart

Design rules	Coating structure	coating / structuring
MID		Wa 02/2005

	2K-injection moulding	Hot embossing	Mask structuring	Laser-structuring	In-Mold-Decoration (IMD)
Cu-coating min.[µm] max. [µm]	1 50	12 150	5 70	9 50	15 70
Surface finish min.[µm] max. [µm]	Ni Au 1 0.1 12 0.8	Ni Au 1 0.1 5 2	Ni Au 1 0.1 12 1	Ni Au 3 0.1 5 0.2	Ni Au 1 0.1 5 1
coating area max. [cm^2]	limited by bath size	lim. by foil and adjoin	2500	400	75% of foil area
z-extension max. [mm]	200	limited by adjoin	230	200	200
Pitch min.[µm]	250	200	125	80	100
Pitch Distance min.[µm]	250	300	125	40	100

Figure 9: Guideline for the limits of manufacturing techology

4 EVALUATION

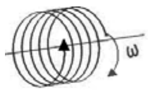
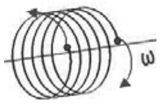
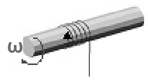
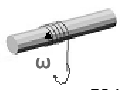
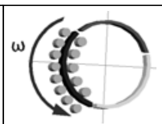
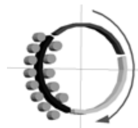
A comprehensive and valid evaluation of a design methodology is very extensive. It would have to comprise at least an intensive use of the methodology in different types of domains, companies, manufacturing technologies and by designers from diverse disciplines and with several levels of experience in design projects. The suggested guideline and the design process were for this reason only applied and evaluated in exemplary MEMS development projects.

A first test of acceptance and usability of the design process was realised by interviews in cooperation with industry partners from different industry sectors. The companies were of different size and possessed different technological background to get a broad repertory of reactions. Guideline, methods and underlying assumptions were presented to and reviewed by designers and process responsible managers. The results confirm the assumptions on which the methodology is based.

Companies judge the interdisciplinarity and the continuously advancing technology as main callenges. Particularly missing or vague requirements at the beginning of the development process often result in system failures and a delay in time. An intensive check of the systems interrelations and an improved cooperation of domain experts or even a “common language” that is supplied by the working structure could improve teamwork significantly.

The general development process of the methodology was evaluated positively, corresponding with the fundamental approach in reality and was “more systematic” than the work flow in real projects. The supporting methods were judged useful, particularly if they provided knowledge or at least a way to structure existing knowledge. Companies emphasised the inevitability of adjusting process and methods to the special needs of e. g. different industry sectors.

The methodology was applied in three academic and industrial development projects. Tasks were the development of sensors for inclination, angle of rotation and air mass. The evaluation showed that the fundamental workflow is applicable and leads to usable results. A clear advantage was the structure of the knowledge e. g. achieved by classification schemes, Figure 10, resulting in the use in additional projects.

<table>
<tr><td colspan="3">Direct procedures</td><td colspan="2">Inductivity:</td></tr>
<tr><td colspan="5">Single cable: $L = \mu_0 \mu_r l \frac{\ln\frac{2l}{r} - \frac{3}{4}}{2\pi}$ Dual cable: $L = \mu_0 \mu_r l \frac{\ln\frac{a}{r} + \frac{1}{4}}{\pi}$</td></tr>
<tr><td>Modified physical value</td><td colspan="3">Single cable</td><td>Description</td></tr>
<tr><td rowspan="2">r</td><td colspan="3">Type of rotation</td><td rowspan="2">The coil has a certain length, both end stay in one plane. Rotation changes radius and distance.
Left: one end fixed
Right: both ends moved</td></tr>
<tr><td colspan="2">
DL1</td><td>
DL2</td></tr>
<tr><td>l</td><td colspan="2">
DL3</td><td>
DL4</td><td>The coil is winded on or off a solid core. This changes the length of the coil.</td></tr>
<tr><td rowspan="2">μ_r</td><td rowspan="2">quantity</td><td>
DL5</td><td>
DL6</td><td>Three different dielectrics change the dielectricity due to rotation of the coil</td></tr>
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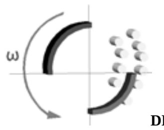
DL7</td><td>
DL8</td><td>Same principle, but only two different materials</td></tr>
</table>

Figure 10: Classification scheme for inclination sensor functions

The results of test and evaluation of the methodology are promising and they open up possibilities of a smoother development of MEMS. Test projects have shown more integrated concepts at earlier stages of the development process, less failures and iterations as well as an early consideration of manufacturing aspects in the design process.

5 Conclusion

MEMS design differs from procedures in other domains. A methodology for the development of MEMS products must be based on MEMS-specific requirements. The close integration of divers domains, technology-driven development and effects of miniaturisation challenge experts from different domains and demand a common view on process and product and an adapted development procedure. This methodology has been missing up to now.

As a step forward, this research work contributes a new MEMS-specific design methodology to fulfill the above demands. It introduces a fundamental development process for MEMS design.

The process has been integrated into product lifecycle and the organisational context of business environment. More specific subtasks have been described exemplarily. The methodology was enriched by methods for the specific demands of MEMS development.

The test and the evaluation of both the proposed MEMS design process and the methods indicate acceptance and usability in practice. Further evaluation in industry is necessary to verify the usability in different application fields.

Acknowledgements

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Contact: Dr.-Ing. Dipl.-Kfm. Robert Watty,
Prof. Dr.-Ing. Hansgeorg Binz
Universität Stuttgart
Institute for Engineering and Industrial Design
Pfaffenwaldring 9
70569 Stuttgart
Germany
Phone: +49 (0)711 685-66040
Fax: +49 (0)711 685-66219
e-mail: robert.watty@iktd.uni-stuttgart.de,
hansgeorg.binz@iktd.uni-stuttgart.de
URL: http://www.iktd.uni-stuttgart.de