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DESIGN CATALOGUES FOR MICROSYSTEMS

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1. Introduction

The demand for miniaturized three-dimensional components that integrate sensing, processing or actuating functions, mainly in consumer electronics, information technologies and automotive industry among many others, has increased the need for a flexible but well defined method to design them. Microsystems and microelectromechanical systems market is estimated to grow with a compound annual rate of 16% to US$ 25 billion in 2009, while products incorporating them will have a global market of US$ 57.1 billion by that time [Wicht et al 2005]. This pushes the development of a microsystem design procedure that could be planned, optimized and verified. Basic rules in this direction are currently being developed, however a lack of scientific tools prevails [Binz et al 2004]. The main research effort in microsystem engineering continues to be the improvement of miniaturization and manufacturing processes. Systematic design is still poorly understood as the application of CAD and FEM software. To fulfil the requirements on quality, time and cost of design under today's competitive conditions the authors searched for a method that could help in introducing systematic product development into MEMS and microsystem engineering. This paper stresses the need for MEMS design catalogues and proposes their implementation to carry out conceptual design. A scenario of practical application is given.

2. Research method

The objective of this work was the finding of a tool to support microsystem designers in the conceptual phase when looking for function structures, function carriers, working principles and principal solutions. It was motivated by the hypothesis that if we cannot trust our experience when things get extremely small, then we should proceed systematically to gain understanding of the working principles of the "microworld".
This article is the result of two main stages:

- A descriptive study, reflected in section 3., in which insight into the peculiarities of microsystems conceptual design was obtained through system analysis and literature research. This segment provided a basis for the decision on selecting an adequate method for supporting microsystem designers.
- A Prescriptive study, in section 4., that represents the results. It offers an scenario of the desired situation and an example of how the idea can be implemented. The assumption was made that implicit knowledge, or the totality of understanding and abilities an individual can apply to solve tasks and problems, is transferable when documented, e.g. registered and structured into explicit knowledge.

A study of the actual impact of design catalogues in microsystem engineering will be part of future work.

3. The problem of microsystems conceptual design

A significant difference between microsystems conceptual design and that of other products lies in the need to consider the corresponding manufacturing processes, since the synthesis of function carriers is dependent on the structuring technology, e.g. silicon-micromechanics, micromachining, LIGA. Additionally, the whole development must contemplate compatibility with the packaging. The sensing and actuating elements have to be protected while keeping them in contact with their operating environment. This problematic results in longer design cycles [Hsu 2002].

Furthermore, microsystems are characterized by interdisciplinarity, heterogeneity and complexity:

Interdisciplinarity means the interrelation between various knowledge domains during the development process. Often interact mechanics, electronics, control engineering, chemistry, biology and others. Interdisciplinarity carries different methods and tools, diverse world views, terminologies and languages. These influences the communication between developers.

Heterogeneity relates to the interaction of system elements from different energy domains with diverse forms of material and information flows, e.g. the integration of biological and mechanical components with electrical ones. It causes incompatibilities, compromises, problematic computation and the need for a variety of description means, models, and simulation methods. Heterogeneity often forces the division of the development process into teams distributed over various departments and even different companies.

Complexity refers to the system behaviour when it is less attributable to external influences than to its own dynamics. Complexity makes the total system behaviour more difficult to describe, even if complete information about single components and their interaction is on hand. This property arise from non-linear interactions and feedback-loops. A close related term is “complicated” but meaning made of many different parts that obstruct the characterization of the structure. These unusual qualities are illustrated by means of an idealized microsystem in Figure 1.

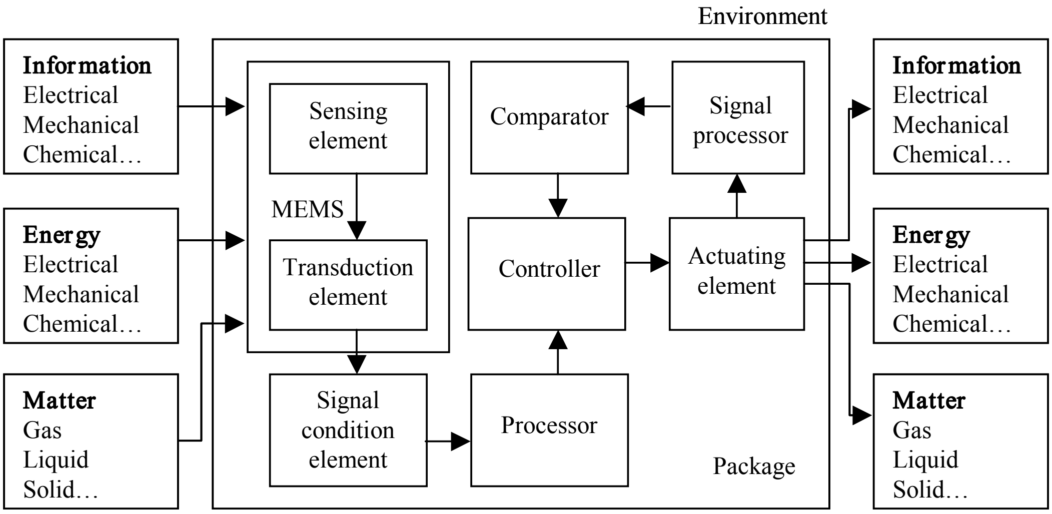


Figure 1. Heterogeneous, complex, interdisciplinary interactions in microsystems

A hypothesis of the authors is that the problem of conceptual design in microsystem engineering lies not only in the described peculiarities, but more significantly in the still lacking knowledge about transforming function structures into function carriers. This is an ability that, e.g. in mechanical engineering, has been perfected through centuries. Microsystems belong to a domain that does not correspond with the sensory organs experience. Microstructures are abstract and hard to see, their form is given optically and chemically, and they function under uncommon physical effects. We must systematically build up our knowledge about their working principles.

3.1 Systematic microsystems design

From machines to mechatronic systems, the principles of methodical design have been elaborated and published in several guidelines. A seminal work is the VDI-Guideline 2221 on a systematic approach to the design of technical systems and products [VDI 1993]. In mechatronics exists a design methodology, the VDI-Guideline 2206. In microsystems there is still work to do. Nevertheless the basics of systematic microsystem design have been worked out in some publications, e.g. the methodology for integrated MEMS design [Garverick 1996] or the design process for conventional microsystems [Menz 2005]. There are three systematic approaches to be recognized from the microsystems development literature: the top-down, the bottom-up and the meet-in-the-middle design. The differences between procedures consist in the origin and degree of enhancement of the solution concept. This means either the concepts are available and optimized or they have to be synthesized.

In top-down design the development goes from the system requirements to a system concept. Then follows the creation of function modules and finally components.

In the bottom-up development the designers begin with an available concept that usually is an optimized component. This will help to build up a function module and many function modules constitute a system.

In the meet-in-the-middle strategy the developers deal with simplified models of already existing component concepts that enable a simulation on system-level under different conditions. Then follows the optimization of features like surface, conductor length, and others.

The top-down procedures is considered the adequate for an optimal microsystem development, because ultimately a microsystem is the synergetic integration of various elements and not a simple addition of separately optimized components. Top-down design permits the enhancement of the whole system as a unit. However, until now, the only practicable approach on various cooperation projects has been the meet-in-the-middle strategy [Menz 2005].

After planning and clarifying the task, the very first step in top-down design is the conceptual phase. Where function structures and working principles that satisfy the requirements are found through analysis, abstraction and synthesis. The result of this stage is the principle solution. That is the reason why in the full introduction of systematic design into microsystem engineering, the accent should be on this phase. The finding of ideas and the working out of solutions could be then carried out by means of methodical tools.

3.2 Design catalogues

A design catalogue is a designer external-memory or knowledge reservoir, that is built systematically on classifying criteria and specific rules [Roth 1994]. Normally it is structured into tables that enable precise access to the contents. A catalogue usually consists of four main parts: classifying criteria, solutions, solutions characteristics and remarks.

The advantage that has made design catalogues prevail as discursive method in mechanical and electrical engineering is that they contain collections of known and proved solutions to design problems on distinct levels of embodiment. Catalogues can cover according to the designer's needs physical effects, working principles, principle solutions, machine elements, standard parts, material properties, or bought-out components. In the past, such data were usually found in textbooks and handbooks, company catalogues, brochures and standards. Some of these contained in addition to purely objective data and suggested solutions, examples of calculations, solution methods and other design procedures. Furthermore, design catalogues provide [Pahl 2003]:

- Quicker, more problem-oriented access to the accumulated solutions or data;
- The most comprehensive range of solutions possible, or, at the very least, the most essential one, which can be extended later;
- Applications independent of specific company or discipline; and
- Data for conventional design procedures as well as for computer-aided methods.

Today, design catalogues are not only available on paper, there are computer-based versions that increase their efficiency using modern data processing technologies, e.g. by implementing hypermedia method for a non-linear multi-modal knowledge representation and usage, so that users can not only browse and navigate through them, but also interact [Franke 2004].

Commercial design and simulation software packages often provide less systematic and not so structured databases called libraries or catalogues, which contain standard components, pre-modelled entities and simulation objects. They do not provide the user with problem-oriented access to design solutions and should not be confused with design catalogues. However, the latter can contain these elements too and more, depending on the implementation media, e.g. bond graphs.

3.3 System view of microsystems peculiarities

All the unusual qualities of Microsystems that have been treated above can be described systematically by means of their interactions. Figure 2. shows an influence model where they are represented as system elements with their corresponding effects.

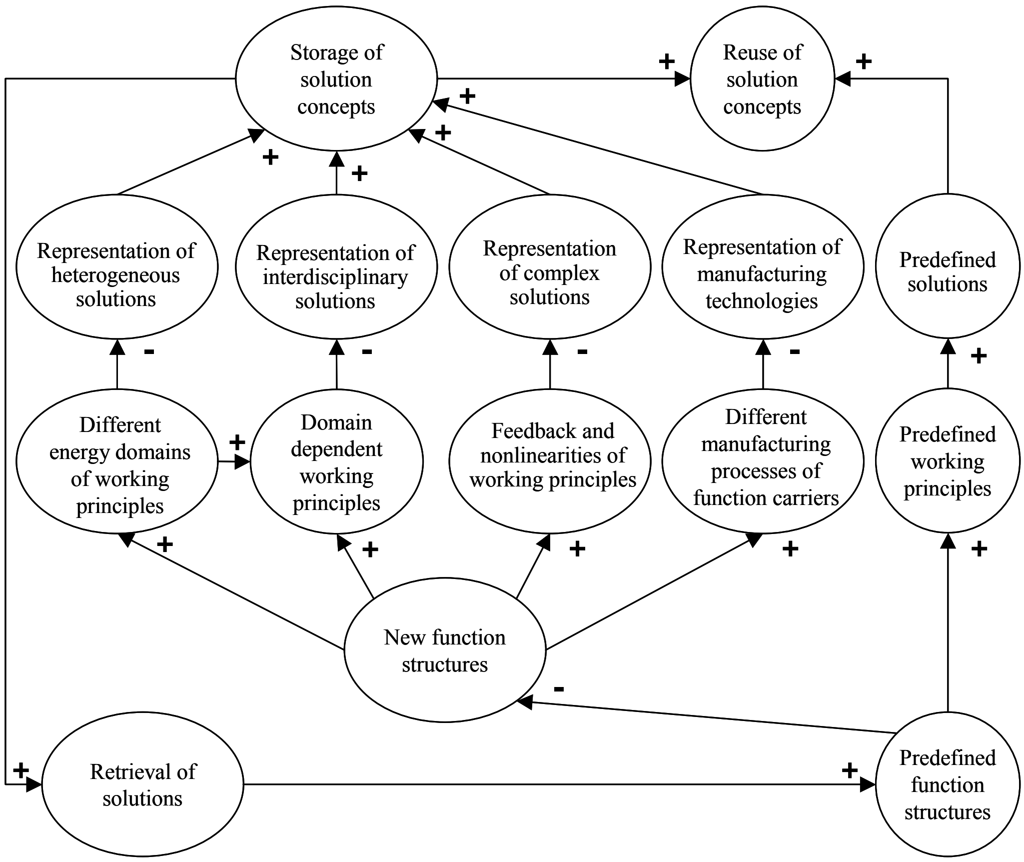


Figure 2. Influence model of microsystems peculiarities

The arrows symbolize directions of influence, while their signs describe the sense of the influence effects. A positive sign means that the effect has the same sense of the influence, e.g. the proposition "if *more* new functions have to be determined, then probably *more* different energy domains will arise out of the working principles" has a positive sign in Figure 2. because the influence-effect relation is of the form "if more…, then more…" (equal senses).

A negative sign signify that the effect is opposite to the sense of the influence, e.g. the statement "if *many* predefined function structures are available, then *few* new function structures have to be determined" has a negative sign in Figure 2. because the influence-effect relation is of the form "if many…, then few…" (different senses).

The most important interrelationships in the influence model are:

1. The storage of solution concepts enables their reuse.

2. The storage is possible only if the representation of interdisciplinary, heterogeneous, and complex solutions, together with the related manufacturing technology is given simultaneously.
3. The more predefined function structures are available, the less new ones must be determined.
4. The less new function structures must be determined, the lower the probability of having to face different energy domains, domain dependant working principles, feedback, nonlinearities and incompatible manufacturing processes.

Further influence analysis reveals the following system element properties.

- Sink – element in which arrows point only inwards: reuse of solution concepts.
- Critical elements – those who have a relative big amount of influences: storage of solution concepts, new function structures, predefined function structures and different energy domains of working principles. In some systems critical elements can be driven externally to control the system behaviour or modify the dynamics.
- Feedback loops – paths that are a closed circuits: e.g. *storage of solution concepts* → retrieval of solutions → predefined function structures → new function structures → different energy domains of working principles → representations of heterogeneous solutions → *storage of solution concepts*. The loop starts and ends in the same system element.
- Critical path – trajectory that unifies a large amount of effects as result of many feedback loops: predefined function structures → predefined working principles → predefined solutions → reuse of solution concepts.

The graphical influence model of Figure 2. has a certain degree of subjectivity because statements about the system behaviour depend on the way the model is read, nevertheless it permits a qualitative analysis of the system dynamics through the feedback loops. Feedback loops can be positive or negative. The sign is obtained by multiplying the signs of the effects in a closed circuit. Positive feedback tends to amplify effects. Contrarily, negative feedback is likely to dampen a sum of effects. Of particular interest for the development of design catalogues for microsystems are all the positive feedback loops that tend to "amplify" the possibility of storing solution concepts, e.g. the loop (storage of solution concepts → retrieval of solutions → predefined function structures → new function structures → domain dependent working principles → representations of interdisciplinary solutions → storage of solution concepts). This is a positive feedback loop according to equation (1) and it makes possible the storage of concept solutions in design catalogues.

$$(+)(+)(-)(+)(-)(+) = + \qquad (1)$$

The conclusion to draw out of the system view of MEMS peculiarities is that intervening in the critical elements by means of design catalogues, designers can get access to the critical path that leads to the reuse of solution concepts.

4. Results

The condition for determining whether a tool is adequate for Microsystems conceptual design is that it must allow the representation of interdisciplinary, heterogeneous, and complex information about engineering structures and their interactions, together with the related manufacturing technology. Additionally, to be practical, it must provide the designer with problem-oriented access to the information. These are conditions that other tools, like libraries, databases, classification schemes, morphological matrices and bond graphs cannot fulfil alone.

4.1 Correlation between microsystem design peculiarities and design catalogues

Roth did not have to deal with interdisciplinarity, heterogeneity and complexity when he compiled the first design catalogues for mechanical engineering. However, it is possible to transfer his method to microsystem engineering because design catalogues and microsystems unusual qualities correlate:

- Microsystems are the integration of different components that perform a specific function as a unit. Design catalogues classify properties of functions and components by differentiation and make them explicit. Behind differentiation there is simultaneously systematic integration.

- Microsystems are heterogeneous. Design catalogues are universal. There are no ruled restrictions on their contents, domains and representation methods.
- Microsystems are complex. Design catalogues can be used to simplify the information about their function structures through partitioning, hierarchisation and modularisation.
- Microsystems are interdisciplinary. The solution to their design problems should be comprehensible to engineers of multiple disciplines in order to facilitate their interaction. Design catalogues can storage multidisciplinary knowledge by means of diverse representations, models and descriptions.

4.2 Scenario of the Desired Situation

According with the influence model of section 3.3., the more new elementary solutions (functions, working principles) have to be found in the conceptual phase, the more probably designers may have to deal with multiple energy domains, discipline dependent problems, feedbacks and nonlinearities, as well as different manufacturing processes for the function carriers. This may be one of the reasons that has established the meet-in-the-middle design as the only feasible microsystems development approach. Striving for a top-down design, developers should be provided with many predetermined elementary solutions, then they will face the mentioned trouble less frequently. For this purpose, out of the four basic types of design catalogues, namely object, operation, solution and relation catalogues, the first three are adequate. Object catalogues are task- independent and contain general knowledge of physical, geometrical, material or technical nature, e.g. Manufacturing processes, physical effects and effect carriers. Operation catalogues are object-related and are conceived to help by building function structures, modifying solutions or relating objects. They include, e.g. design rules, rules for calculations and procedures for selecting solutions. Solution catalogues are task-dependent and according to the degree of embodiment they associate tasks to functions, functions to effects, effects to carriers, effect carriers to forms and forms to manufacturing processes.

For an example of the application of design catalogues in MEMS design, imagine the following scenario. A designer is given the task of developing a concept of a pressure sensor. The problem lies in structuring Single Crystal Silicon (SCS) to fulfil the function of a membrane. In the firm, due to technical reasons, other materials are out of the question. See Figure 3.

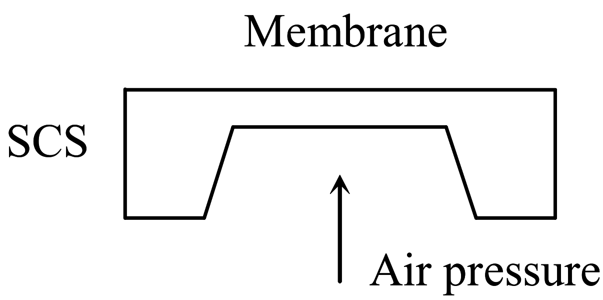
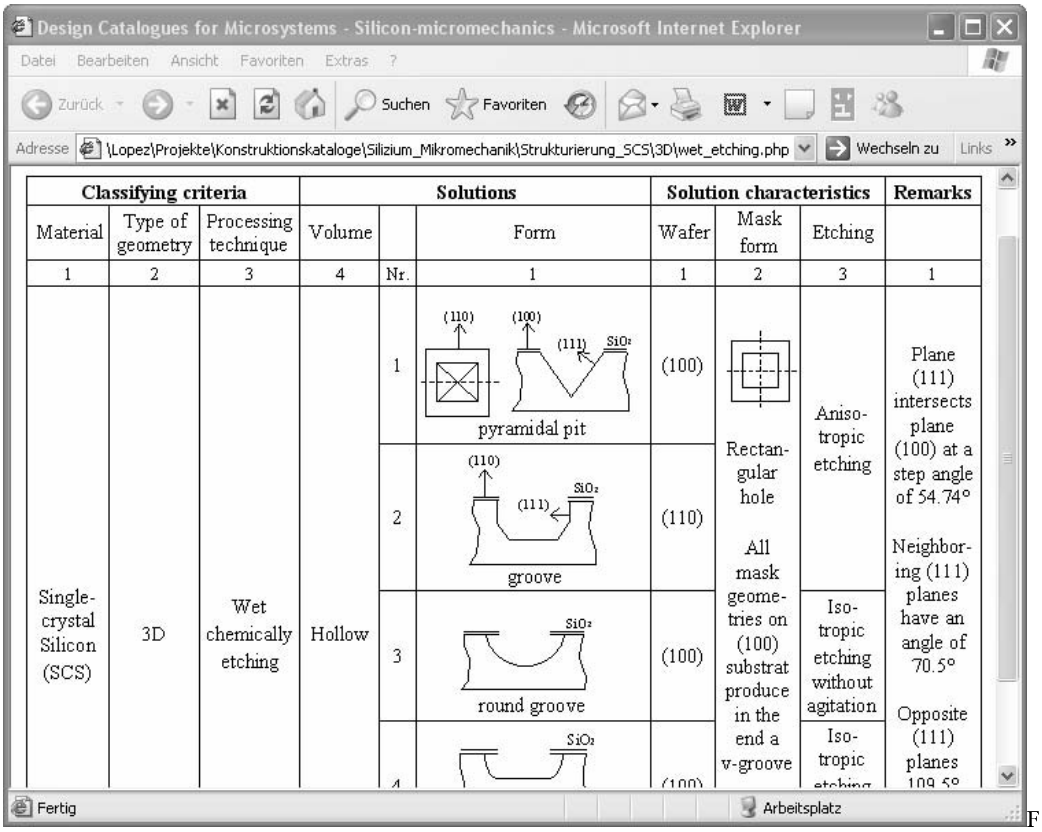


Figure 3. Membrane of single crystal silicon

As it can be seen in the catalogue excerpt of Figure 4., for the problem of giving a SCS a three-dimensional hollow form a proved solution is the wet chemically anisotropic etching with a rectangular hole mask. More information, like the wall angles of the cavity, is contained in the remarks. Thus, the catalogue helped to integrate the functional, technological and manufacturing aspects of the problem within the design process. Figure 5. represents the process flow.

In a complicated scenario, new objects, operations and solutions may arise that should be added to the catalogues in order to expand their content. This *knowledge expansion* is represented in Figure 5. by the dotted arrow.



Classifying criteria			Solutions			Solution characteristics			Remarks
Material	Type of geometry	Processing technique	Volume		Form	Wafer	Mask form	Etching	
1	2	3	4	Nr.	1	1	2	3	1
Single-crystal Silicon (SCS)	3D	Wet chemically etching	Hollow	1	(110) (100) (111) SiO2 pyramidal pit	(100)	Rectan-gular hole All mask geome-tries on (100) substrat produce in the end a v-groove	Aniso-tropic etching	Plane (111) intersects plane (100) at a step angle of 54.74° Neighbor-ing (111) planes have an angle of 70.5° Opposite (111) planes 109.5°
				2	(110) SiO2 (111) groove	(110)			
				3	SiO2 round groove	(100)		Iso-tropic etching without agitation	
				4	SiO2	(100)		Iso-tropic etching	

Fgure 4. Design catalogue for microsystems – Silicon-micromechanics (excerpt)

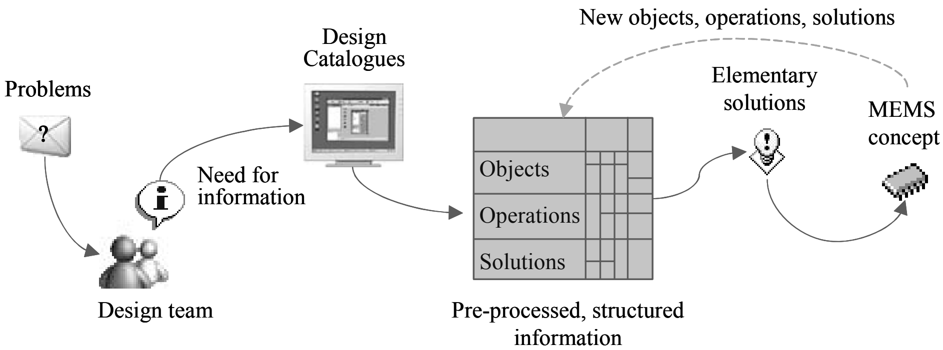


Figure 5. Process flow of MEMS conceptual design with design catalogues

A foreseen application of design catalogues is to assist microsystem engineering in education and self-learning. Placing hypermedia design catalogues on an active-server would allow an interactive distribution of knowledge, turning them into a computer-tool for online self-study and online training. Knowledge anywhere and anytime could diminish the pressure of project deadlines [López 2005]. Figure 4. is also an example of a hypermedia implementation.

The independence of design catalogues regarding disciplines and companies may offer designers with no microsystem engineering curricula a tool that facilitates the understanding between engineering fields. Consequently, support in the integration of effective interdisciplinary project teams could be achieved. Additionally, microsystems industry could display with design catalogues a knowledge-management strategy by means of retrieval of known solutions and recording of new knowledge, promoting so the exploitation of expertise and creativity as production factors.

6. Conclusions

Design catalogues match the nature of microsystems. They can contain heterogeneous knowledge, describe complex interactions and represent them in understandable ways to multiple disciplines. They make accumulated knowledge explicit and help to transfer it, supporting so the creativity of designers. Furthermore, due to their problem-oriented accessibility, they are practical. Their use in microsystems conceptual design, where experience is still insufficient, should be emphasized. They can contribute to the cultivation of engineering abilities that are critical in microsystems development. Ultimately, the quality of innovative products depends on the skills of their designers.

Acknowledgement

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References

Binz, H., Kück, H. et al., "Improved design and development process for MEMS sensors". Proeedings of Eurosensors XVIII Conference, Rome, September 2004.

Franke, H.-J. et al, "Increasing the efficiency of design catalogues by using modern data processing technologies", International Design Conference - DESIGN 2004, Dubrovnik, 2004.

Garverick, S.; Mehregany, M., "Methodology for Integrated MEMS Designs", Proceedings of the IEEE International Symposium on Circuits and Systems, Atlanta, 1996.

Hsu, T., "MEMS & Microsystems – Design and Manufacture", McGraw-Hill New York, 2002.

López, J.A., Binz, H., "Design Catalogues As Knowledge Management And Educational Tools In Microsystem Engineering Design", Proceedings of the 15th International Conference on Engineering Design, Samuel, A. ed., The Institution of Engineers, Melbourne, 2005, pp. 614-615.

Menz, W., Mohr, J., Paul, O., "Mikrosystemtechnik für Ingenieure", WILEY-VCH Verlag Weinheim, 2005.

Pahl, G., Beitz, W., "Engineering Design – A Systematic Approach", Wallace, K. ed., Springer Verlag London, 2003.

Roth, K., "Konstruieren mit Konstruktionskatalogen", Vol. 2, Springer Verlag Berlin, 1994.

VDI-Guideline 2221, "Systematic Approach to the Design of Thechnical Systems and Products", Verein Deutscher Ingenieure Düsseldorf, 1993.

Wicht, H. et al, "NEXUS Market Analysis for MEMS and Microsystems III, 2005-2009", European Microsystems Network ed., Wicht Technologie Consulting Munich, 2005.

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