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ASPECTS OF HIGH INTEGRATION IN MEMS TECHNOLOGY

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1. Introduction

The domain of MEMS (Micro-Electro-Mechanical-Systems) is far beyond other technologies, e. g. microelectronics or mechatronics, characterized by a broad variety of different devices. They are manufactured in nearly arbitrary shapes using several kinds of materials and technologies.

MEMS technology deals with the integration of diverse micro technologies in complex and highly integrated systems under continuously developing boundary conditions. Typical products, e. g. sensors, are used in a broad variety of application fields from the automotive to the medical technology industry and the MEMS market is actually growing with 20% per year.

MEMS mass products are characterised by interaction of diverse disciplines integrated in one product, e. g. micromechanics, microoptics, microelectronics, biology or chemistry. The diversity of involved technologies, the close integration of components of diverse domains and the simultaneous development of product and manufacturing process influence the development process. The integration of diverse domains and the interrelations between them require the incorporation of skilled specialists from different knowledge fields. Interrelations and interactions in highly complex systems must be considered in an appropriate way [Kasper] and require effective support of designers [Eurosensors]. An extensive study of MEMS design by Klaubert [Klaubert] emphasises the need for guidelines for geometry, manufacturing and materials as well as assistance in the understanding of the entire system.

This paper suggests a possible development process and methodical support of designers by a new developed integration method to help experts of various fields to achieve efficient and effective product development.

2. Development of MEMS

MEMS technology originally developed from the technology of integrated circuits in microelectronics. Microelectronics deal with automatically developed two-dimensional structures whereas actual MEMS devices usually include non-electrical subassemblies and usually comprise a three-dimensional design.

MEMS are defined as miniaturized discrete objects with integrated sensors, signal or information processing and actuators with characteristic dimensions in the range of few micrometers [Kasper].

Components consist of functional and geometric elements, e. g. beams, diaphragms or bearings. The fundamental structure of MEMS is shown in picture 1. Miscellaneous components are assembled on a silicon substrate, e. g. electrically or optically connected and enclosed by a housing.

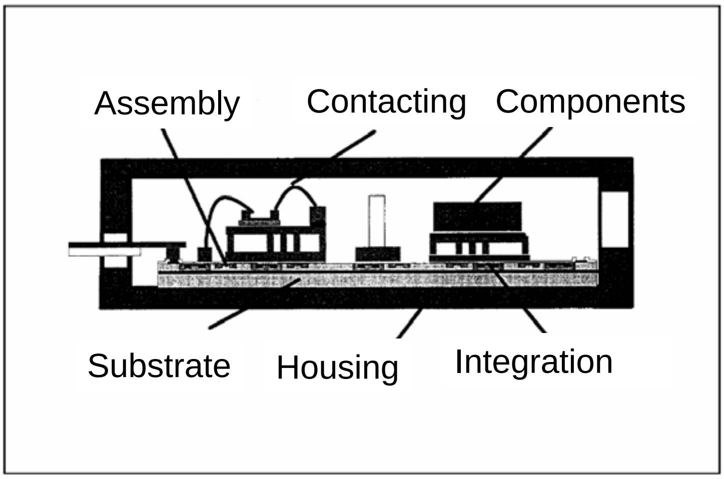

Figure 1. Fundamental structure of MEMS, based on [Reichl]

MEMS technology deals with the design, manufacturing and appcliation of such systems [Kasper] and closely integrates diverse disciplines of physics, e. g. micromechanics, microelectronics, microacoustics, microoptics and microfluidics, as well as microbiology and microchemistry, Figure 2.

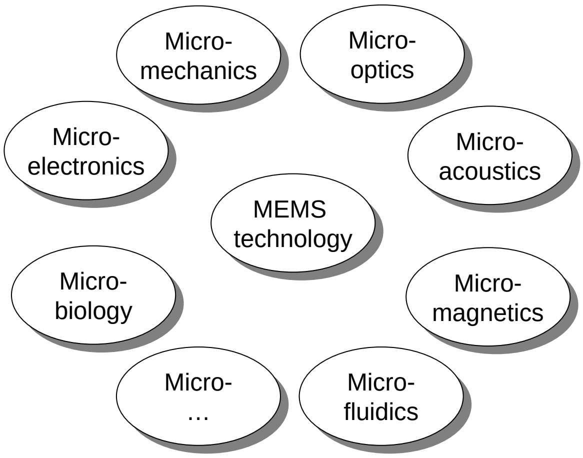

Figure 2. MEMS disciplines

The miniaturisation of existing or the development of new elements in compact dimensions enables the integration of various elements in a small volume. It also provides new technical principles and properties concerning e. g. inertia or power consumption. Last but not least it serves the demand for continuously decreasing costs that is very important in most of the application fields.

On the other hand the miniaturisation increasingly leads to the limits of manufacturing technology, causes influences between MEMS components and results in physical effects of miniaturisation. A smaller surface-volume-ratio may cause cooling problems and the mechanical properties of a system may change due to the fact that specific mechanical stiffness increases with smaller dimensions [Roth]. Electromagnetic effects enable electrostatic micromotors but also cause lubrication problems or deflection [Gilbert] and undesirable parasitics in small systems. MEMS require not only efficient components but also their correct interaction to fulfil the function of the entire system.

The diversity and the continuous modification of technologies, materials and applications challenge the designer. He must verify assumptions and consider new influences when he designs highly integrated technical system. A good understanding of physical background, material, manufacturing

process, overall concept and desired signal transmission become essential preconditions for a change of dimensions. The complexity caused by number and variety of elements and interactions requires experts of diverse disciplines to solve development tasks.
The reduction of these impacts requires their consideration in the development process by use of adequate methods accepted by designers in practice. Support for interdisciplinary teamwork and the realisation of interfaces is demanded but not sufficiently available.
A proposal for a new MEMS design methodology based on the VDI guideline 2206 [VDI2206] for development in mechatronics is shown in Figure 3.

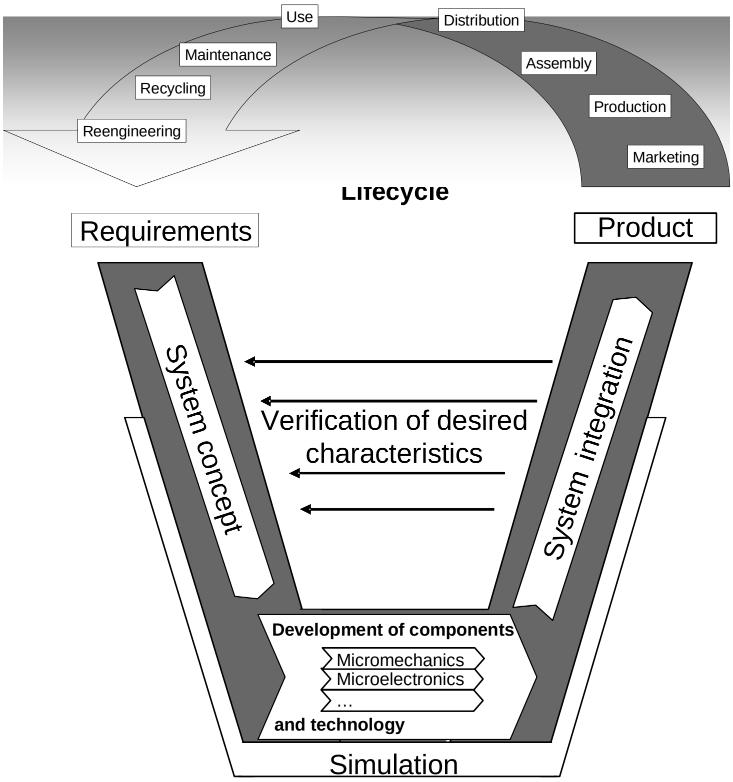

Figure 3. Development process for MEMS

This general development process starts with the generation of a interdisciplinary system concept. 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. The concluding system integration verifies 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 products life. Simulation as early as possible helps to predict the properties of the system and supports both integration and supply of efficient technology.
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. The development process is therefore characterised by iterations. The consideration of parasitic influences and the simulation of the system and its components at an early stage is one way of forecast of properties and prevention of iterations. The described general process must be precisely specified and adapted for the demands of specific product developments.

Required powerful tools and methods for the examination of the entire system beyond single components and domains are missing up to now [Binz]. Developing a system the conventional way of bottom-up based on a main component lacks the system view, the top-down approach has to deal with missing information about components and their realisation in the beginning. It is advisable to follow a meet-in-the-middle strategy alternating between bottom-up and top-down with increasing maturation of the system [Kasper]. The aspect of integration must be supported by adequate methods in all phases of the development process.

3. The working structure as integration method

The importance of the geometric and material parameters for the function of mechanical, electronical and optical design was pointed out by Jung [Jung]. He introduced the “geometry function principle” and constituted the importance of the correlation between geometric and material parameters as well as internal and external influences for the function of a system, Figure 4.

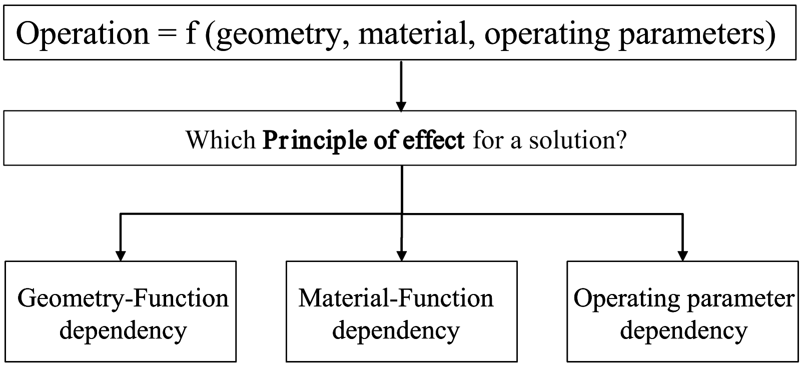

Figure 4. Principle of effect, based on [Jung]

In order to consider all influences and interrelations, it is necessary to get a clear view of the geometric combination of fundamental elements as well as the effects of used materials and influencing operation parameters. The relation between geometry and function is essential for the development of MEMS, but different from other technical areas [Klaubert]. The function structure established in mechanical engineering enriched by geometrical, material and operation characteristics of the solution enables a comprehensive view on MEMS and their internal and external functional interrelations.

The new developed working structure for MEMS supplies a system view beyond the functional aspects covered by the function structure. It illustrates geometric and material parameters of the components of a system and their mechanical connection. Connections are illustrated by symbols representing their degree of freedom, Figure 5.

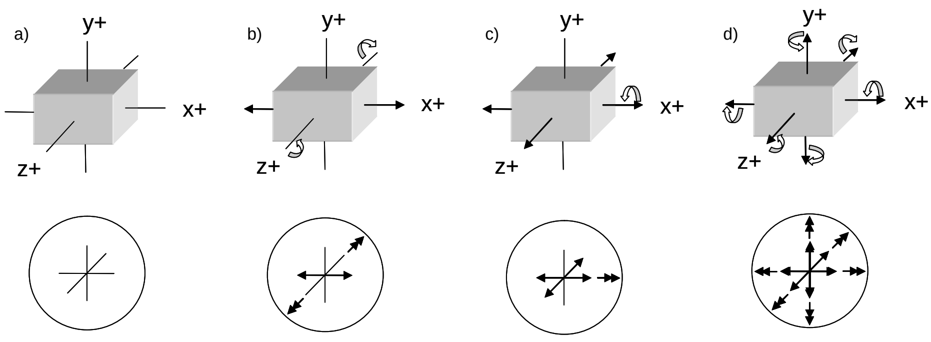

Figure 5. Illustration of rotatory and translatory degrees of freedom

Illustration (a) shows a fixed connection without possible motion. Full rotatory and translatory motion is represented by (d), whereas (b) and (c) allow partly translatory and rotatory movement.
This graphical representation of a system is supplemented with internal and external influences. Figure 6 shows the new developed working structure of an rotary incremental encoder as an example.

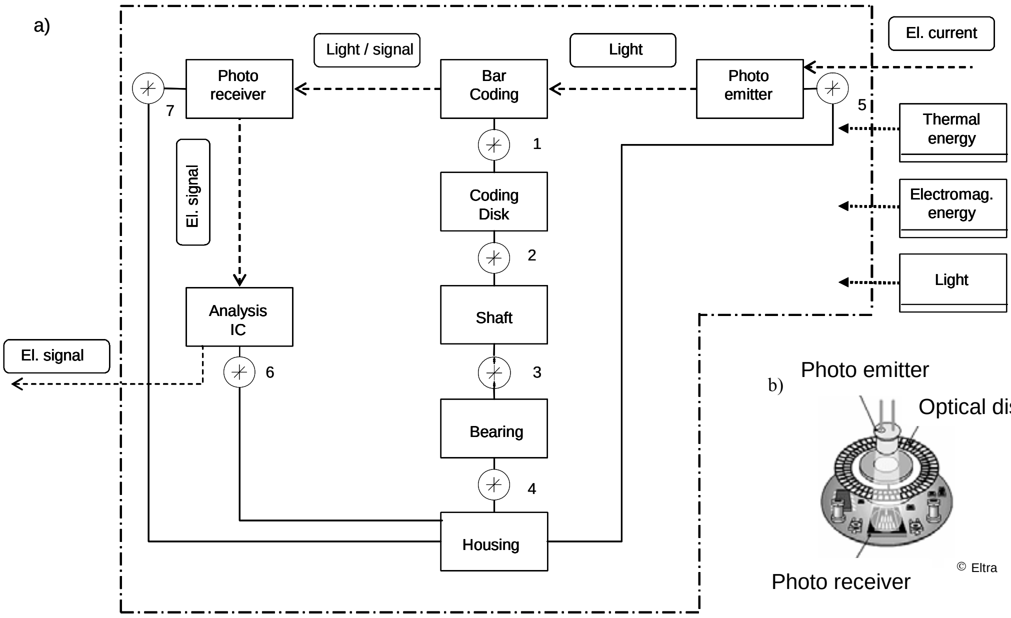

Figure 6. Rotary incremental encoder
a) working structure
b) functional principle

The illustration by the working structure supplies a holistic view on complex systems and can be completed by more precise descriptions of elements during the development process. This complete overview of all components of a MEMS enables the review of system elements and their interrelations during the development process.
Thus this new working structure contains far more information than the function structure and allows an intensive observation of the total system during the entire development process.

4. Review of system interrelations

The analysis of e. g. physical, geometrical or functional interactions between components of the system and its environment is supported by a matrix based on the working structure.
The Design Structure Matrix (DSM), also known as Dependency Structure Matrix is a compact matrix representation of a system or project. DSM was initially introduced by Warfield [Warfield] and used in numerous cases, e. g. for the integration of large scale systems by Eppinger [Eppinger]. The DSM consists of a sequence of system components that are represented in the same order in both row and column of the matrix. The central part of the matrix shows the dependencies between the components.
The integration analysis of a system consists of three steps [Eppinger]:

- Record the system configuration
- Document the interactions in a matrix
- Analyze the matrix to identify the structure of interactions

The DSM represents the system structure and helps to get a clear view of its configuration. Figure 7 illustrates the DSM for the working structure of the rotary incremental encoder in Figure 6.

Design **S**tructure **M**atrix	Nature / material	Photo receiver	Bar coding	Photo emitter	Coding disk	Analysis IC	Shaft	Bearing	Housing	Connection 1	Connection 2	Connection 3	Connection 4	Connection 5	Connection 6	Connection 7	El. Current	Light current	Light / signal	El. signal	Thermal energy	Electromag.energy	External light
Photo receiver				←												←		←	←			←	←
Bar coding		←		←	←	←					←										←		
Photo emitter		←												←			←						
Coding disk			←							←	←												
Analysis IC		←	←												←					←	←	←	
Shaft					←				←		←	←											
Bearing	radial						←		←			←	←								←		
Housing	plastic	←		←	←	←		←					←	←	←	←		←	←		←	←	←
Connection 1	lasered		←		←																		
Connection 2	adhesive				←		←														←		
Connection 3							←	←															
Connection 4								←	←														
Connection 5				←					←														
Connection 6	adhesive					←			←														
Connection 7		←							←														
Light current				←					←														
Light / signal		←	←	←	←				←														
El. signal		←				←																←	
Thermal energy								←	←														
Electromag.energy		←		←	←																		
External light																							

Figure 7. Design Structure Matrix of a rotary incremental encoder

All parts, connections, flows and external or internal influences are documented in the rows and columns of the matrix. The nature or material of one of these parameters can be added in the beginning or during the structure identification process. Influences and interactions are documented by arrows pointing to the parameter in the column. Thus all influences on e. g. a system component become quite obvious by considering the corresponding row. On the other hand all influences coming from e. g. an external influence like thermal energy are centralized in one column. The matrix also shows components and their direct connections by shaded fields.

This enables the designer of a component to consider all influences and to be sure to gather all information from other domains influencing his work. Furthermore it helps mechanic, optic and electronic designers to work together and to find interrelations between them and to e. g. manufacturing engineers.

Development process, working structure and Design Structure Matrix were evaluated in three development projects and in interviews with development departments of 5 companies. The results showed that the methodology is usable in practice, based on valid assumptions and focused on the main problems of MEMS design. The described methods were applied with very good results. The experience proved that more aspects were considered in order to optimise quality, overall function and manufacturability of the developed MEMS. A main advantage pointed out by designers in practise was the supply of a common language for interdisciplinary problems and the identification of possible parasitic influences and interrelations at an early stage of the development process.

An advanced step incorporates a computer-aided optimisation by identifying dependencies not only qualitatively but also quantitatively. The separated view on the system from different physical impacts must be separated in the DSM in a first step, figure 8, resulting in a 3-dimensional matrix. The matrices contain e. g. only thermal or electromagnetical aspects to support specific simulations and point at relations between the different views.

Design Structure Matrix	Nature / material	Photo receiver	Bar coding	Photo emitter	Coding disk	Analysis IC	Shaft	Bearing	Housing	Joint 1	Joint 2	Joint 3	Joint 4	Joint 5	Joint 6	Joint 7	El. Current	Light current	Light / signal	El. signal	Thermal energy	Electromag.energy	External light
Photo receiver				←												←		←	←			←	←
Bar coding		←		←	←	←					←										←		
Photo emitter		←												←			←						
Coding disk			←							←	←												
Analysis IC		←	←												←					←	←	←	
Shaft					←				←		←	←											
Bearing	radial						←		←			←	←								←		
Housing	plastic	←		←	←	←		←					←	←	←	←		←	←		←	←	←
Joint 1	lasered		←		←																		
Joint 2	adhesive				←		←														←		
Joint 3							←	←															
Joint 4								←	←														
Joint 5				←					←														
Joint 6	adhesive					←			←														
Joint 7		←							←														
Light current				←					←														
Light / signal		←	←	←	←				←														
El. signal		←				←																←	
Thermal energy								←	←														
Electromag.energy		←		←	←																		
External light																							

structure

thermal view

electromagnetic view

Figure 8. Design Structure Matrix with different views

In the next step dependencies must be described by integrated formulas and simulation. Computer aided tools for specific problems are highly developed and powerfull means for simulation in several domains.The use of CA-systems is therefore widespread in the macro world. MEMS development requires the consideration of both very small dimensions and a high integration of diverse disciplines that calls for an integrated approach. Up to now there is a lack of suitable CA-systems that are able to simulate interdisciplinary development tasks in the geometrical dimension of MEMS.

5. Conclusion

MEMS development differs significantly from development in other domains. It requires not only adapted development processes but also appropriate methods to enable the development of products with high quality at reasonable prices.

A fundamental development process for MEMS development has been introduced. A new method for system integration of MEMS based on working structures and DSM matrices simplifies the consideration of integration aspects important for MEMS development. This method can be transfered to other domains dealing with system aspects, e. g. mechatronics.

The results obtained are promising and the evaluation of the developed guideline showed acceptance and usability in practice.

The high grade of integration requires further support of the development process by appropriate methods. The integration of interdisciplinary systems should be enriched by use of computers to gain a deeper understanding of the systems interrelations and to store and provide this knowledge for further projects.

The relatively new and expanding field of MEMS technology becomes more and more structured, but there are still many white spots on the map.

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