Approaches to the Design of Micro Mechanical Systems

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Abstract
The design and manufacture of micro mechanical systems is characterised by a multi-disciplinary environment. The use of established design approaches such as axiomatic design, functional analysis and biomimetic design can be used in the conceptual design phases. The concept of micro engineering is introduced to identify important characteristics of the design and secure a coupling to manufacturing possibilities at an early stage. The paper discusses the different design approaches applied to micro mechanical systems and illustrates some issues based on specific cases.

Keywords:
Design, Micro manufacturing, Micro mechanical system

1 INTRODUCTION

Innovation within the field of micro and nano technology is to a great extent characterized by cross-disciplinary factors. The traditional disciplines like physics, biology, medicine and engineering are united in a common development process that can only take place in the presence of multi-disciplinary competences [1]. This requires a high degree of scientific specialization both from the point of view of the product designers and the production specialists. This fact makes the principle of concurrent engineering quite hard to implement. This paper describes some of the challenges related to the design of micro mechanical systems. Selected case examples will be used to illustrate the complexity of this area.

2 MICRO MECHANICAL SYSTEMS

A micro mechanical system is characterized by small dimensions, either of the system/component itself (one or more critical dimensions) or of functional features or structures on the system/component [2]. Generally, two categories of micro components are identified:

- Components with at least two critical dimensions in the sub-mm range, thus implying that the parts themselves are small and usually with a very low mass, e.g. parts for hearing aids.
- Relatively large components with functional features in the µm range, e.g. DVDs.

This viewpoint itself makes a clear-cut definition hard, since features by nature can be one or more orders of magnitude smaller than the dimensions of the products.

From a geometrical point of view micro products can be organised into three groups [2]:

- Two-dimensional structures (2D), such as optical gratings.
- 2D-structures with a third dimension (2½D), for example fluid sensors (the structure of the channel system itself is two-dimensional, but since the channels have a finite depth they can be characterised as 2½D).
- Real three-dimensional structures (3D), for example components for hearing aids.

The geometry affects the possible manufacturing methods and the associated production support in terms of handling, assembly and metrology.

Another important characteristic of micro products is integration: integration of functions, integration of different functioning principles (physical, chemical, biological etc.) and integration of intelligence into products in terms of information processing and control (sensors and actuators).

The integration of different length scales into the same component/product is discussed in [3]. Here length scale integration is defined as the integration into a single product of functional features of different characteristic scales, e.g. nano structured surfaces on a micro fluidic device. Two different types of "solutions" to this problem are identified in [3]: assembly related solutions and multi-scale machining solutions. Solutions are linked to the absolute dimensions in question. If the critical dimensions are in the sub-mm range (as defined previously in this section) typically assembly solutions are identified to deal with length scale integration. If the absolute dimensions become so small that physical manipulation is difficult (due to force interaction, loss of visual coordination etc.) standard solutions are not available and other principles need to be employed (e.g. self assembly etc.). Assembly can to some extent be avoided if all manufacturing processes can be performed on the same specimen. Solutions employing a single process on multiple scales are seen (e.g. micro electrical discharge machining) as well as multiple processes on multiple scales (e.g. application of two processes in sequence). In both cases process resolution, alignment and referencing errors as well as process realization become key challenges.

3 DEVELOPMENT OF MICRO MECHANICAL SYSTEMS

3.1 General considerations

The process of coming from the first idea to an industrially manufactured product is long and must eventually include engineering skills. The ideas for functionalities to be obtained via micro products stem from many scientific areas. This will challenge the ability of engineers to create functional products and to choose between the many possible solutions. Some common mistakes during concept development encompass the following points:

- Consideration of few alternatives and failure to consider other concepts employed
- Ineffective integration of promising partial solutions
- Failure to consider entire categories of solutions

These points are valid for macro products but become particularly relevant in micro product development since the designer often is limited by a specific scientific background. The integration of semiconductor technologies with conventional manufacturing technologies and material science represents the biggest challenge to micro product development but also the most promising trend in terms of innovation and value creation.

The generic product development process (figure 1) can be adapted to micro products with some modifications [4-5]. Early in the process special considerations have to be given to material choice and the subsequent manufacturing technology. If the principle structure is based on a fixed combination of materials and related production technologies (e.g. silicon and etching technologies) the subsequent development becomes an optimization of this combination [6]. In this case no real possibilities exist for changing materials or processes, thereby influencing product performance and cost. A premature choice of materials and processes also limits the possible geometries to be used for the single parts/components (2D-2½D-3D). Therefore the designer and product developer have to possess knowledge about alternative materials and production technologies to be able to develop the most optimal product for a given situation. A way to reduce development time and cost is through a systematic design approach to reach a decoupled design solution.

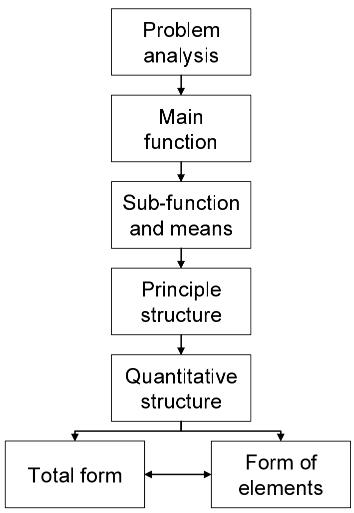

Figure 1: Generic product development process [5].

3.2 Systematic design approaches applied to micro systems

In any micro manufacturing technology and particularly in silicon micromachining, the manufacturing sequence influences the technical performances and quality of the product. Therefore, several constraints due to incompatibilities of materials, processes and geometries have to be considered while defining a manufacturing sequence [7]. Since each process step influences, in principle, the results of both the previous and the following process steps the process sequence has to be checked for consistency and incompatibilities must be identified. Eventually this will influence the design parameters. According to [8], the possible constraints due to incompatibilities can be grouped into three classes.

First the properties of material or functional elements may be affected by succeeding processes as for instance twisting or destruction of delicate mechanical structures due to thermally induced mechanical stresses or the attack of thin film materials by subsequent etching processes. The second class comprises the possible negative influence of the properties of materials and device geometry processed so far on the quality of succeeding technology steps. Again, examples are insufficient adhesion of adjacent thin film layers or inadequate planarity of layers deposited on top of 3D micro structures. The third kind of constraints concerns the feasibility of generating the intended device geometry using the specified fabrication processes. Even though the references refer to silicon based technologies, in principle the same types of constraints and incompatibilities are seen in micro manufacturing of components in polymers and metals as well.

A way to reduce development time and cost is through a systematic design approach to reach a decoupled design solution using the axiomatic design approach [9]. In fact, depending on the sequence of processes and process steps, a MEMS design can be coupled or decoupled. In many cases designers are not conscious of the coupled nature of their design and thus it becomes difficult to identify the correct changes in the process variables to improve (or even to obtain) the product performances. Often the process variables to fabricate MEMS devices are “randomly optimized”. In [10] the axiomatic design approach is used to design and manufacture a MEMS based device.

A systematic method based on functional analysis as described in [11-12] can also be used. A method based on the analysis of a macro scale device, followed by an analysis of which functions are influenced by the downscaling can be used. This approach has proven to be beneficial in pinpointing problem areas induced by downscaling.

Finally, the use of biomimetic approaches has been reported in micro product design [13]. Biomimetic design uses biological phenomena as analogies to help solve engineering problems. One well-known example of biomimetic design is the development of Velcro after observing that cocklebурs attach to clothing and fur. The use of this methodology requires access to biological databases and the competence to interpret and translate analogies into engineering solutions.

4 MICRO ENGINEERING APPROACH

Micro engineering is introduced as a concept and it should be seen as the entire set of actions related to product development and manufacturing of micro products. In this context it becomes clear that a categorization as proposed above is not sufficient to comprise a full definition of the product. Important aspects such as geometrical complexity, integration of various materials, functionalities and components as well as requirements concerning mechanical, chemical and electrical performance all should be considered during the process of product development. This phase is strongly influenced by a lack of design guidelines and tolerancing rules, and it is complicated by the fact that the tradition of concurrent engineering is far from dominating the development phase in micro engineering. The use of standard construction elements as in traditional mechanical engineering has until now not been adapted intensively although some commercial MEMS CAD tools contain standard elements such as beams and cantilevers. The fundamental issues of size effects when trying to apply macro rules to micro products and components are big e.g. [14]. In consequence, no uniform approach exists in this field, the consequence being that product developers run the risk of being limited to ‘known traditional solutions’ only.

The current research in the micro manufacturing area is focused very much on single manufacturing processes and their interaction with the materials being processed. Focus is given to size effects e.g. [2,14]. The establishment of coherent process sequences, i.e. covering all necessary process steps from tooling over replication to assembly processes, is a very important research area. Often it is a quite challenging step and for the industrial realization of micro manufacturing a necessary step. When integrating single processes into coherent process chains and subsequently into production systems issues as material compatibility, relative accuracy, alignment precision, etc. must be considered. The necessary actions related to quality control comprise process validation and verification of tolerances as specified in the design.

Figure 2 illustrates the necessary components in a micro engineering approach identifying the most challenging parts. By experience some of the most restricting elements are the coupling of manufacturing possibilities (and constraints) to a conceptual design. This is where the specificities of micro scale processing are implied onto the design. Possibilities and restrictions of processing are described in many papers e.g. [15-18], but a major challenge is to establish an overview in order to make a qualified decision. So far the systematic design approaches described earlier only lead you a part of that way.

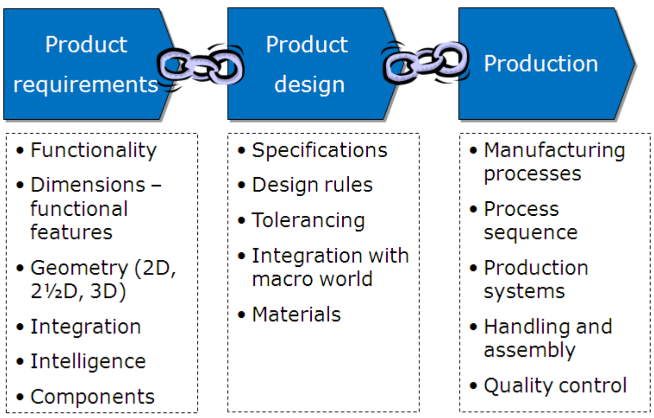

Figure 2: Elements in the concept of micro engineering.

Another challenge for micro product design is the detailed specification in terms of dimensioning and tolerancing. In macro scale engineering this discipline is well established and a long tradition has enabled distributed manufacturing based on a common technical terminology. In micro manufacturing, this is still an emerging area. The support from technical standards is virtually nonexistent at these scales. Furthermore, in a standard manufacturing environment, dimensional metrology is used to ensure the quality of the produced components. If the micro mechanical system is based on assemblies, extremely high demands are set to positioning and alignment accuracies in-between process steps as well as precise parts for subsequent assembly steps. This concept requires detailed knowledge of not only absolute dimensions and geometrical quantities, but also about the uncertainty of measurement, because this is a decisive parameter when dealing with mating capability in general.

In this context the verification of tolerances by means of dimensional and geometrical metrology becomes a key point. The specifications are usually given in terms of maximum deviations from an ideal, nominal dimension/form. The compliance with specifications are described in [20]. Figure 3 illustrates the principle. In order to be able to decide about a specific part, two points need to be fulfilled: a suitable measurement method must be identified to perform the measurement and the corresponding measurement uncertainty needs to be sufficiently small to be able to verify the tolerance. Upon downscaling of the absolute dimensions, usually the ratio of measurement uncertainty to tolerance becomes large, in this way leaving a smaller conformance zone for process variations.

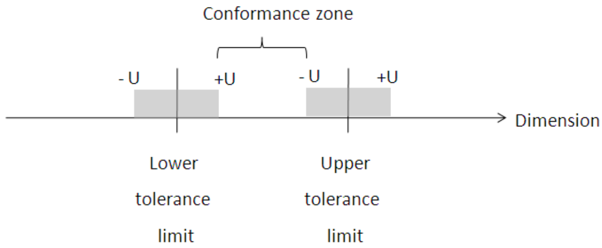

Figure 3: Tolerance verification at micro scale. “U” indicates measurement uncertainty.

5 RE-DESIGN OF SWITCH FOR HEARING AIDS

In hearing aids many micro electro mechanical systems are found. This case is based upon a so-called push button found in many so-called “in-the-ear” solutions (figure 4). The push button can be used to turn on/off the system or change programs in the IC. The maximum diameter is 1.9 mm. As illustrated in figure 4, the current system is based on the scaling down of a traditional mechanical solution: screws, springs and structural elements. The single elements are manufactured using standard down-scaled manufacturing technologies, and the assembly is performed in a semi-automatic way. The chosen design is robust from a performance point-of-view, and experience shows relatively little sensitivity of the single manufacturing tolerances on the subsequent assembly. The turning process (for making the 0.5 mm screw) is close to the limit of state-of-the-art. The main challenge in the entire process chain lies in the assembly operation. Manual labour is required because a fully automated assembly line is too inflexible (typical production volume 100.000 pieces /year).

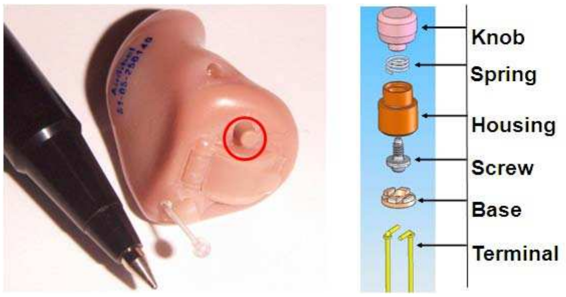

Figure 4: Push button for hearing aid applications.

Applying the proposed methodology to the push button has resulted in a new proposed design and process chain [21]. Based on the list of specifications, an analysis based on functional analysis was performed. In parallel, possible processing scenarios were screened in order to be able to take advantage of new technological possibilities in the design phase. It was decided to opt for a solution based on two-component micro injection moulding. Figure 5 illustrates the principle. A core part consisting of two polymers, of which one has been metallised, secures the electrical conductivity from top to bottom. A flexible dome attached to an outer housing creates the electrical contact. The dimensions mentioned are about 2 times larger than the existing solution. This was chosen because of the challenges related to physical realisation of the tools. Figure 6 illustrates the plastic part after injection moulding of the two polymer materials. The material combination was chosen in such a way that chemical metallisation of the second shot polymer was possible (without any metal being deposited on the first shot polymer). This is a compromise between establishing a strong adhesion between the two polymers and securing a selective metallisation. These two characteristics are acting in opposite directions [21]. The new design consists of 4 main elements compared to the 6 of the original design. With the proposed process chain, complexity in manufacturing was moved from the assembly steps to the injection moulding step. Furthermore, an extra metallisation step was introduced compared to the traditional solution.

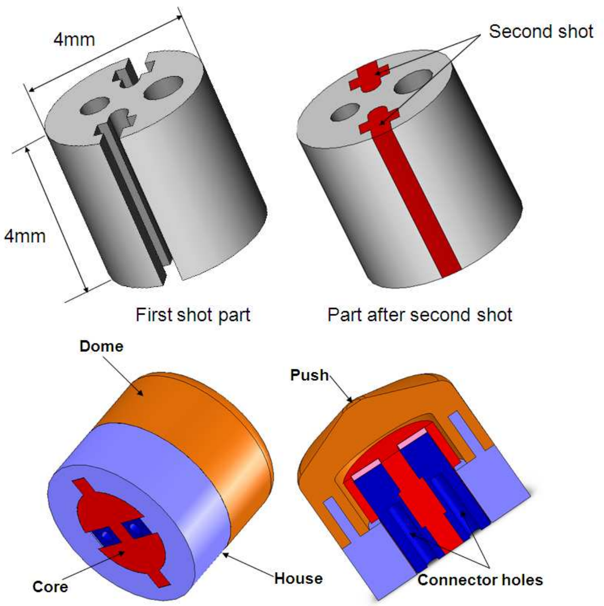

Figure 5: Concept of design based on two-component micro injection moulding. Top: core. Bottom: assembly of core, house and dome.

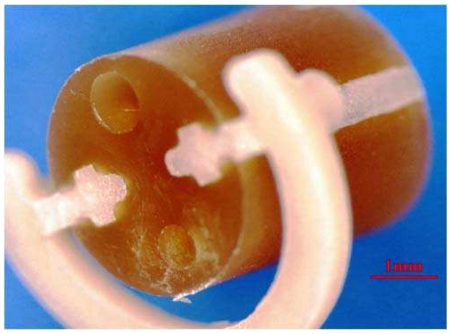

Figure 6: Two-component plastic part.

6 TOLERANCE VERIFICATION AT MICRO SCALE

In the following section, an example of tolerance verification of a micro polymer part is given. The work is partly based on [22]. The part under investigation is a polymer part as illustrated in figure 7. It has four measurands of interest: the inner diameter of the centre hole (d, 1.550 ± 0.020), the outer diameter (D, 5.400 ± 0.030), the concentricity between the two circles (C, 0.020) and the height of the pillar in the bottom of the picture (H, 0.380 ± 0.030).

The dimensions are not all sub-mm, but the tolerances are all in the µm- range. The tolerance verification in an industrial environment was based on methods and equipment where the uncertainty to tolerance ratio was ranging from 20% to 70%. This made the verification virtually impossible.

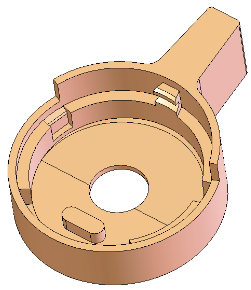

Figure 7: Illustration of toggle for hearing aids.

The challenge in this situation is to establish a basis for quality assurance that gives a reasonable conformance zone. By experience the golden rule of the gauge maker (stating that the measurement uncertainty should not be more than 10% of the tolerance zone) cannot be met at this scale. Figure 8 illustrates three main sources of variations that contribute to the overall variation. Enough space should be left for being able to detect process variations, and the only way this can be obtained is be reducing (as much as possible) the variations introduced by the instruments and the metrology procedure.

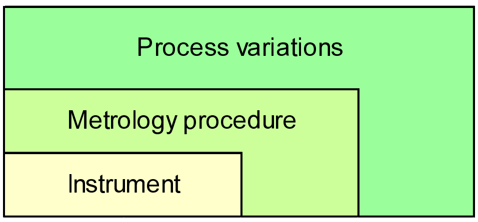

Figure 8: Sources of variation in measurements related to manufacturing.

In the present case the metrology procedure was changed from the traditional approach based on the use of calibrated instrumentation to a substitution method [22]. Figure 9 illustrates the two principles. The first method, in this case, resulted in too large uncertainties compared to the tolerance intervals. By choosing the substitution approach, the measuring instruments were "only" used as comparators. The main source of uncertainty would come from the calibration of the reference artifact/workpiece. In this case, a high precision tactile coordinate measuring machine (TCMM) was used. These results yielded extremely good U/T values (see figure 10). However, the TCMM is slow, so an optical coordinate measuring machine (OCMM) was employed using the substitution method close to the production. Figure 10 shows two results for the OCMM: one result obtained "as is", and one result obtained after compensating for a systematic error. The systematic error is introduced by the fact that the reference workpiece is calibrated using the TCMM and the measurements related to the production obtained using the OCMM. The two different measuring principles yield different results. It is clear that the choice of the correct metrology procedure highly influences the capability of verifying tolerances on micro scale.

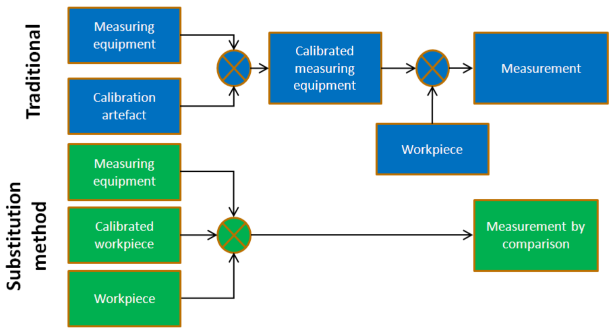

Figure 9: Metrology procedures applied in micro manufacturing. Top: method based on calibration of instrument. Bottom: method based on comparison with calibrated artefact.

	Measurand			
	d	D	H	C
	Average U / T %			
TCMM	12.4	1.5	2.0	4.6
OCMM / no-comp	46.5	10.5	123.8	40.9
OCMM / comp	17.3	4.6	33.4	14.9

Figure 10: U/T values obtained using TCMM, OCMM without compensation of systematic errors, on OCMM after compensation of systematic errors.

7 SUMMARY

The design and manufacture of micro mechanical systems is characterised by a multi-disciplinary environment. The use of established design approaches such as axiomatic design, functional analysis and biomimetic design can be used in the conceptual design phases. The concept of micro engineering is introduced in this paper to identify important characteristics of the design and secure a coupling to manufacturing possibilities at an early stage. The paper discusses the different design approaches applied to micro mechanical systems and illustrates some issues based on two specific cases.

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