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INTEGRATED DESIGN AS AN APPROACH TOWARDS DFμMA

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1. Introduction

The application of miniaturized devices and systems in the physical world is at an ever increasing pace. Some specific application of the miniaturized systems can be addressed as in micro actuators, optical components, medical devices and automotive industry [Ehmann et al. 2002]. The Micro products can be categorized into three groups from a geometrical point of view [Alting et al. 2003]:

- Two-dimensional structures (2D): optical gratings are examples of these types of structures.
- 2D-structures with a third dimension (2½D), such as fluid sensors in which the structure of the channels is two-dimensional and the finite depth of the channels are characterized as ½D.
- Real three-dimensional structures (3D), components inside the hearing aid are considered as three-dimensional products.

For the purpose of obtaining an applicable final product in micro manufacturing there are a number of barriers which should be addressed. Issues such as scaling effects on manufacturing, effects of the manufacturing processes on the micro structure, impacts of the micro structure on the processes, accuracy, production quantity, handling and assembly and cost issues are some of the challenges in manufacturing of micro scale products [Ehmann et al. 2002].

In the following sections, the objective of the DFA methodology is briefly reviewed and subsequently, the problems and challenges of the micro products assembly are discussed. This will be followed by a discussion on the necessity of applying DFA in micro manufacturing. As the next step, the two mentioned case studies are described and analyzed. Finally, the improved idea for each case study is presented.

2. Development of DFA methods

The aim of DFA is to make the product simpler to:

- ease the assembly process,
- reduce the assembly costs and total part cost [Boothroyd et al. 1992] (by reducing the number of components that need to be assembled),
- Ensure that the remaining components are easy to assemble and manufacture,
- And fulfill functional requirements [McCluskey et al. 2009].

The application of DFA methods is mainly on assembly of the products with part dimensions from a few millimeters up to several decimeters [Eskilaender et al. 2004]. The most common DFA methodologies can be named as Hitachi Assemblability Evaluation Method, the Lucas DFA Evaluation Method and the Boothroyd-Dewhurst DFA Method [Tietje et al. 2007a]. The main principles of design for assembly are to [McCluskey et al. 2009]:

- Simplify the design and minimize the part count

- Use the common materials and available parts and standardize the components
- Mistake-proof product design and assembly
- Design for parts orientation and handling
- Reduce the number of flexible parts and interconnections
- Design for ease of assembly by minimizing the number of axes of assembly and use of simple patterns of movement
- Create well-organized joining and fastening
- Design modular products to facilitate assembly

3. Challenges in micro assembly

Among the challenges in micro manufacturing, assembly of the micro products is quite critical element in the fabrication process. Assembly is the act of constructing a piece of machinery or a group of machine parts that fit together to a self-contained unit [Gegeckaite 2007]. Different functions need different materials and geometries in the same device. The necessity of having flexible or stiff, isolating or conducting materials, and the need for regular replacement of the worn out parts are some of the reasons why products may consist of different parts [Brussel et al. 2000]. The main difference between the assembly of the micro scale and macro assembly is the required positional accuracy of automatic assembly machines [Brussel et al. 2000].

Another significant difference between macro assembly and the micro scale is associated with the scaling effects and the mechanics of object interactions [Brussel et al. 2000]. Micro scale forces such as van der Waals, surface tension forces and electrostatic forces are dominating over gravitational forces. So, manipulation in micro scale is completely different from manipulation in the macro level, meaning that if the dimension of the part is less than one millimeter the adhesive forces between gripper and the handled part can be dominant over the gravitational forces [Tietje et al. 2007b]. Additionally, in the manual assembly, creating direct hand-eye coordination by the operator is a challenging issue. This is due to the limited ability of directly seeing and handling the object under the microscopes and tools [Brussel et al. 2000]. Cost of manipulation is also a problem in micro world when a high percentage of the manufacturing costs are related to the assembly process [Hesselbach 2000], [Koelemeijer 1999].

4. DFA in the micro domain

The applicability of the existing DFA rules is examined in [Eskilaender et al. 2004] and it is concluded that most of the design rules in macro DFA can be used also for micro DFA. However, it is stated that investigating all the existing design rules is not possible. It is also mentioned that the critical parts of the assembly process (such as handling, feeding, gripping) have to be updated and some specific design principles are required [Eskilaender et al. 2004]. The need for a micro specific DFA methodology is underlined in [Hsu 2005], [Tietje et al. 2007a], [Tietje et al. 2007b], and in reference [Tietje et al. 2007b] a DFμA (Design for Micro Assembly) methodology is proposed. Additionally, in [Bullema et al. 2003] a DFμA approach is described based on a verified interconnect and packaging technology towards cost effectiveness.

The optimization of functionality is not targeted in the proposed approach. In spite of the efforts in defining micro specific DFA rules, there is still a lack of rules for design of micro products in early stages. Most of the issues such as manufacturability, assembleability, functionality or performance and economics have roots in the phases of idea generation and selection of final idea among the many proposed ide. Therefore, the more precise and stronger the design is, the less problems and deficiencies will arise in the final result. In the micro-domain, the need for a systematic and specific design methodology becomes more crucial based on the micro characteristics [Ehmann et al. 2007]. The challenges in assembly and manufacturing of micro-scale products make the design process more complicated. Having the DFA rules, specifically for micro scale objects, provides the opportunity for designers to propose ideas based on an efficient methodology with higher precision and less failure.

5. Redesign of micro products by DFA approach

In order to evaluate the applicability of the DFA guidelines in the design for micro scale products and to find out where a set of micro specific principles are required to be defined, two case studies are investigated. The case studies are provided and redesigned by the co-authors and are discussed in this paper as examples to study the need for DfμA rules.

Reducing the number of components, as one of the DFA principles, results in less assembly steps and consequently fewer complications, risks , variety of materials, and lower costs. A proposed solution to the problem of having several components is to combine the components into unified parts. Integrating the functions into a single part is also a way to cut down the component count. As a solution to integrate the functions, manufacturing techniques could be changed for fabrication of the components. The selection of manufacturing processes is highly dependent on the design in the conceptual phases when an idea is under development. It means that from the very beginning the design has to be oriented in the direction of manufacturing techniques with a high potential of integration. The fabrication processes such as 2k injection moulding, moulded interconnect devices (MID), insert moulding and additive manufacturing are examples of technologies where different components can be united into a single part to obtain the functionality.

In the following section, the problems associated with assembly of an on-off switch in hearing aid devices and the optical components of the mobile phones camera are investigated. The redesign procedures of these two case studies along with the improved ideas are also presented.

6. Case study

6.1 On-off switch for hearing aid devices

A standard on-off switch (push button) in hearing aid devices (produced by Sonion A/S) is chosen as the case study in this paper. For both in-the-ear and behind-the-ear devices, switches like push buttons are needed to change between the different programs in the hearing instrument [Webpage of Sonion 2013]. The button is an example of a real 3D micro object.

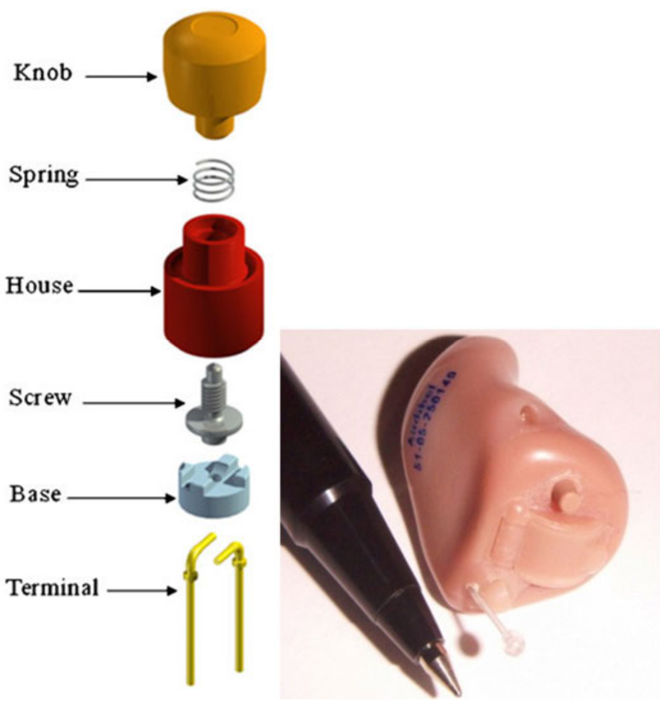


Figure 1. On-off switch produced by Sonion A/S of 7 different components [Islam et al 2009]

The switch is maximum 2.5 mm in diameter with 3.5 mm height. All the objects are axis-symmetric and designed in a way to fit each other [Gegeckaite 2007]. Figure 1 presents the different components of the switch and shows the switch mounted in a hearing aid device. As illustrated in Figure 2, the switch consists of seven different components which are assembled through 11 different assembly steps [Islam 2008]. For this push button, most of the assembly operations are done manually and all the manual operations are accompanied by a microscope. Besides, a specifically designed carrier is used to hold the parts during the assembly process. The characteristics of the switch components are given in Table 1 [Gegeckaite 2007].

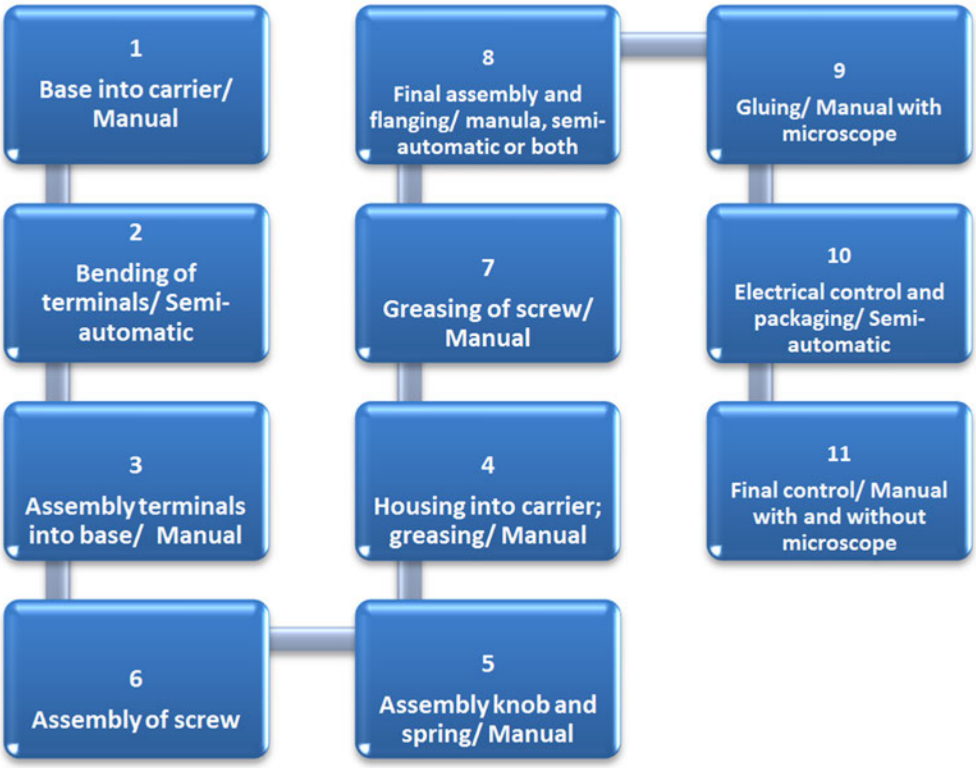


Figure 2. Different assembly steps for on-off switch ([Islam 2008], [Gegeckaite 2007])

Table 1. Specifications of the push button components

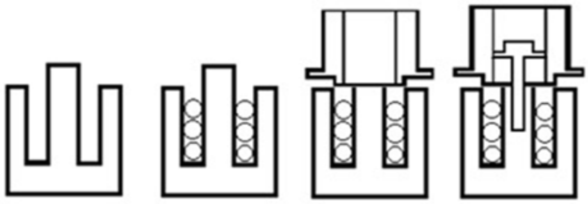
Part number	1	2	3	4	5	6 &7
Name	Knob	Spring	House	Screw	Base	Terminals
Dimension	Ø1.85 x 1.9	Ø1.12 x 1.5	1.9 x 1.85	1.69 x 0.5	Ø1.63 x 0.55	Ø0.2 x 11
Geometry	3D	3D	3D	3D	3D	3D
Material	POM	Cr - Ni	PA	Nickel silver, Au coating	PEEK	Silver, with Au flesh
Manufacturing technique	Injection moulding	Coiling	Injection moulding	Turning and cutting	Injection moulding	Wire drawing cutting

6.1.1 Assembly scenario of the switch

The micro components of the push button are assembled by manual operation and semiautomatic stations. The problems associated with the assembly of the components are as followings [Gegeckaite 2007]:

- Alignment of the parts
- Placement of the parts
- Assembly possibilities

Depending on the assembly method (i.e. side to side, top to bottom, bottom to top) the components have to be connected to each other. Figure 3 lists a possible assembly process of the knob, spring and house along with a schematic illustration [Gegeckaite 2007].



a. The spring is placed into the knob
b. The house is placed on top of the knob (a)
c. The screw is inserted into the house
d. The screw is screwed through the house and spring into the knob
e. The screw is greased
f. Terminal are bent
g. Terminals are inserted to the base
h. Gluing is done on the assembled components
i. Electrical control and packaging are done
j. Final control is performed

Figure 3. Assembly through the top to bottom method [Gegeckaite 2007]

According to [Gegeckaite 2007], the most challenging issues during the assembly steps are identified as:

- Grasping the micro components by the gripper, results in plastic deformation.
- It is difficult to grasp the spring and find a suitable grasping force or even separate then from each other in order to place them in the house holes.
- Due to the small dimension of the terminals and the need for bending of them, placement of the terminal is among the most challenging assembly operations. Assembly of the terminals takes almost twice as long time as the other manual assembly operations.
- The number and the variation of the components in terms of dimension and the material create a complexity in the products and make them difficult for assembly.

6.1.2 Improved design of on-off switch

Considering the difficulties associated with the micro assembly, and the costs of every assembly step, the on-off switch has the potential to be enhanced. The new design of the switch consists of three main components: core, house and dome as shown in Figure 4. The one which is the most technical part is fabricated through 2k injection moulding by combining two different plastic materials. One of these is appropriate for electroless metal deposition and creates the conductive tracks. Consequently, a selective metallization is also applied.

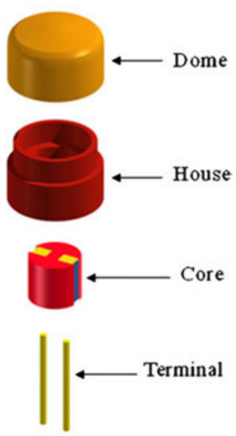


Figure 4. New concept of the on-off switch; from top to bottom: dome, house, core and terminals [Islam et al 2009]

The encapsulation of the entire parts is provided by a dome-shape housing which is placed on top of the core. The house is realized via an ordinary injection moulding process. The dome is made of electrically conductive flexible rubber (e.g. rubber filled with carbon black or silicon rubber) through the injection moulding process, and by pressing it, the two ends of the metallic tracks get connected and the current can flow through the circuit [Islam et al 2009].
The selected manufacturing chain for the new design of the push button is appropriate for mass production. The proposed design has a great potential to replace the old version [Islam 2008].

6.2 Optics

The second case study is the glass optical elements in a mobile phone camera.
The production of high quality optical unit in glass involves two main process steps: moulding and assembly. Traditionally, the glass optical elements are formed in a pressing operation under high temperature (up to 600 °C) and high pressure (usually applying a protective atmosphere or vacuum). Each lens is made one at a time [Brinksmeier et al. 2013]. Requirement of the geometrical compliance is below 1 μm and the average surface roughness needs to be less than 20 nm Ra. The assembly operation is necessary for combining the single optical elements into functional units to be mounted in mobile phones (Figure 5). The assembly involves efforts in aligning the optical elements horizontally and vertically with respect to each other in order to minimize image distortion. The assembly process is complicated and there is a minimum height that can be achieved from the final optical system, and this height might be critical to the use in smart phones.

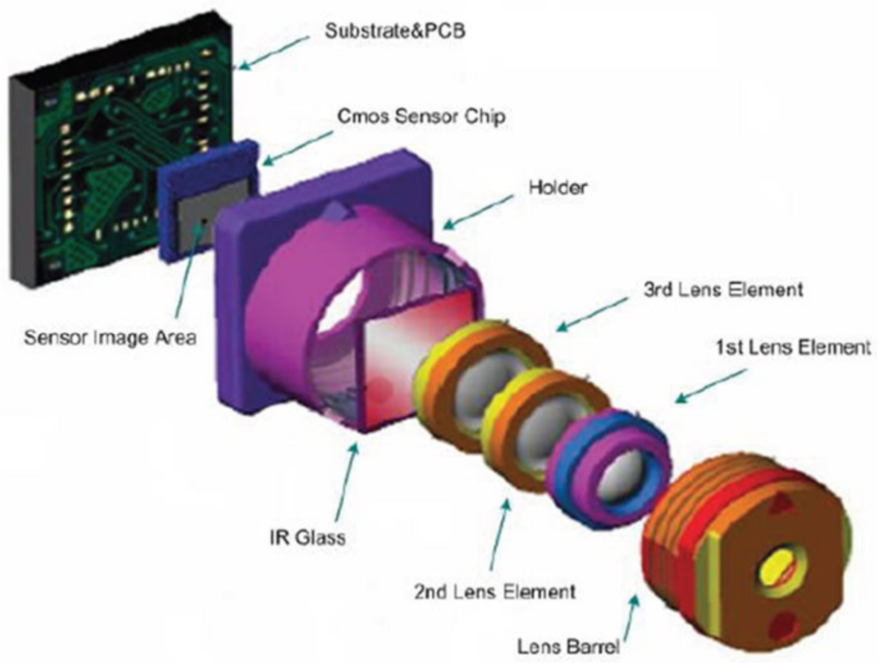


Figure 5. Exploded view of a conventional camera module for smart phones [www.ulightech.cn]

6.2.1 Improved design by wafer based glass optics

A new process was proposed based on simultaneous moulding of many optical elements on a glass wafer [Sarhadi et al. 2012]. Wafer based glass moulding allows simultaneous moulding of hundreds of lenses on a flat polished glass wafer in a single pressing step, thereby enhancing the productivity of the glass moulding process. In addition wafer based moulding allows stacking, aligning and bonding of several moulded wafers, so that ,by a single aligning and dicing operation, several hundreds of finished lens modules can be obtained with a tremendous impact on the overall module cost [Bissacco et al 2011].

The idea is to mould many optical elements on a wafer and then use the wafer to transport and align the optical (see Figure 6). By handling glass wafers instead of single lenses, assembly operations are simplified, but also an extra process step of dicing is introduced. The lens module consists of two glass lenses. The conventional solution then requires the two lenses to be individually mounted in a lens barrel and aligned with the CMOS sensor underneath. In the wafer based glass optics solution, the finished lens module is directly mounted on the CMOS sensor. The Alignment of the individual lenses is not necessary anymore and only the complete lens module has to be aligned to the CMOS sensor in the final mounting operation.

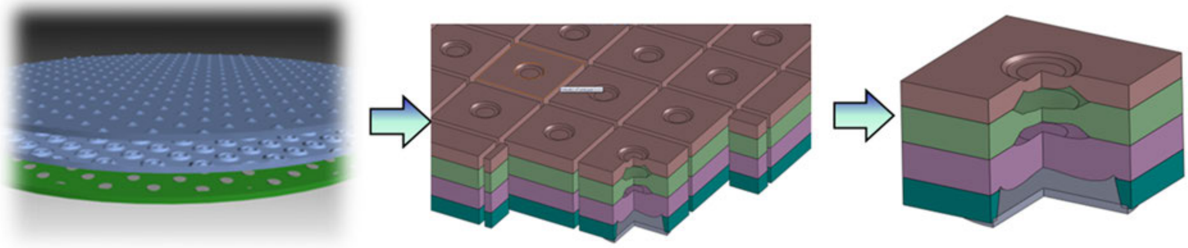


Figure 6. Representation of the wafer based moulding concept introduced by Kaleido Technology [Bissacco et al 2011]

Since accurate positioning of each single lens on the tool is critical for the alignment accuracy during assembly, complexity is thus moved towards the moulding process. A highly complex tool construction is required in order to avoid problems caused by thermal expansion and contraction. Figure 7 displays a prototype mould for wafer level moulding of glass lenses for a camera phone application.

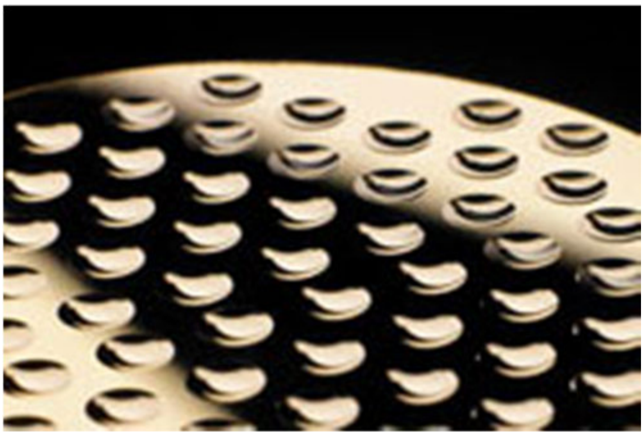


Figure 7. Detail of glass moulding mould for wafer based glass moulding [Webpage of Kaleido 2013]

7. Discussion

In order to evaluate the proposed designs for an on-off switch and an optical unit, the improvement or failure of them has to be checked against the DFA guidelines. Table 2 depicts the assessment of the proposed solutions considering the DFA rules.

As presented in Table 1, considering the DFA rules, the suggested designs for both cases are noticeably improved compared to the original designs. Therefore, “design for integration” and “design for specific micro manufacturing techniques” can be considered as tools to adopt the design to the DFA principles and ease the micro assembly.

Table 2. Evaluation of the proposed design based on the DFA principles

DFA Principles	On-Off Switch		Optical unit	
	Original Design	Proposed Design	Original Design	Proposed Design
Simplify the design and minimizing the part count	_ _	+ + +	_ _ _	+ + +
Use the common materials and available parts and standardize the components	+ + +	_	+ +	_
Mistake-proof product design and assembly	_ _	+ + +	_	+ +
Design for parts orientation and handling	_ _ _	+	_ _	+ + +
Reduce the number of flexible parts and interconnections	_ _ _	+ + +	_ _ _	+ + +
Design for ease of assembly by minimizing the number of axes of assembly and use of simple patterns of movement	_ _	_	_ _ _	+ + +
Create well-organized joining and fastening	_ _ _	+	+	+ +
Design modular products to facilitate assembly	_ _ _	++	_	+ + +

8. Conclusion

Manufacturing constraints in micro domain and complications in assembly of the micro parts highlight the need for a micro oriented DFA methodology. Compared to the aim of DFA method for macro domain which is to ease the assembly process and reduce the costs, DFµA principles have to be defined in a way to assure the assembleability and manufacturability which may end up in cost reduction. In fact DFµA rules should increase the feasibility of realization in micro manufacturing.

The feasibility of the design in micro level relies on the potential of the proposed design for realization, and realization itself is dependent on the availability of manufacturing techniques and assembling methods. Therefore, manufacturing and assembly are not separable. They have a great inter-dependency in micro domain i.e. a product cannot be completely fabricated if it is not assembleable. Hence, a DFµMA (Design For Micro Manufacturing and Assembly) methodology is required as a feasibility assurance during the design phase.

“Integration” is proposed as an essential tool to provide more feasibility in micro manufacturing through reduction of component and material count and consequently the number of assembly steps, which result in a lower cost. Combining different components and make unified parts or integrating different functions into the less number of parts would increase the achievability of the design.

Design for some specific micro fabrication techniques (e.g. 2k injection moulding, insert moulding, wafer based moulding, additive manufacturing) can be a powerful tool to be used in the early stages of design for micro products. These techniques have the capability of combining different materials and components into integrated parts and provide the possibility of merging different functions.

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