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PATTERN-BASED INTEGRATIVE DESIGN OF MOLDED INTERCONNECT DEVICES (MID)

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1. Introduction

Products of mechanical engineering and related industrial sectors, such as the automotive industry, are more and more based on the close interaction of mechanics, electrics/electronics, control engineering and software engineering, which is aptly expressed by the term mechatronics. Modern automobiles, machine tools or airplanes are examples for mechatronic systems or consist of such subsystems.
Basically two categories of mechatronic systems can be distinguished (Figure 1). The first category deals with the controlled movements of multi-body systems. The focus lies on the controllers to improve the system behavior by using sensors to collect information about the environment and the system itself. The second category is based on the spatial integration of mechanics and electronics. The aim is to reach a high density of mechanical and electronic functions within the available space. Such electromechanical parts, which we call mechatronic integrated devices, are very often the basis for the first category of mechatronic systems (e.g. integrated sensors) [Feldmann 2009].

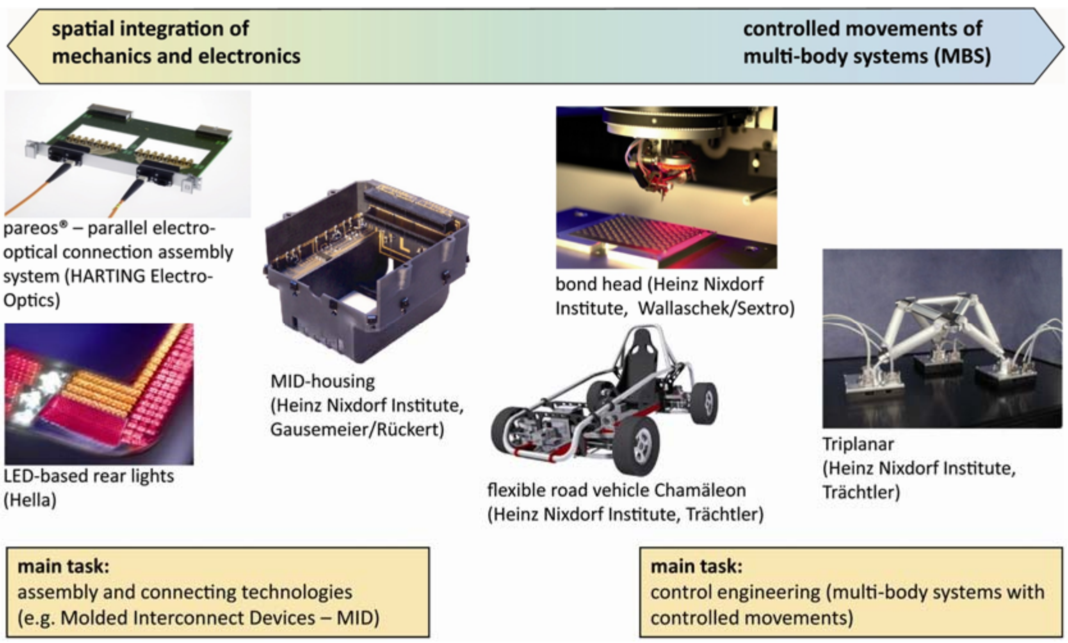


Figure 1. Categories of mechatronic systems

Within the development and production of such integrated mechatronic devices, requirements with regard to miniaturization, function integration, reliability and design are rising. Innovative technologies are necessary to meet these requirements. In this context the technology MID (Molded Interconnect Devices) is very promising. MID enables developers to design innovative components for mechatronic systems. By the integration of mechanical and electronic functions on one single interconnect device, packages with high functional density and considerable miniaturization can be realized. Applications from different industrial sectors like communication, automotive or medical industry illustrate the potentials and the high design flexibility in opposition to conventional technologies (e.g. flexible printed circuit boards).
However the potentials are accompanied by various challenges within the development. These result on the one hand from strong dependencies between the design of the product and its production system; multifarious product requirements compete with restrictions of different manufacturing processes. On the other hand, a close interaction between electrical/electronic and mechanical design needs to take place. The developer has to overcome these difficulties to generate an optimal product concept. For this reason several design methodologies have been developed that should support developers with goal-oriented instructions for the design of MID-products. The disadvantage of these existing methodologies is the limited approach on the creative developing process itself. Directives for distinctive manufacturing processes are given instead of a variety of best practices. Therefore a new concept based on design patterns will be presented covering theses handicaps and supports the developer in the early stages with a range of development options.
This contribution is structured as follows: Section 2 will give a brief survey of the technology MID including a description of the main process technologies and the state of the art of existing approaches for the development of MID-products. Our new concept based MID design patterns will be introduced and explained in section 3. In section 4 we will present an application example for our approach. Eventually, we will conclude our work and give a short outlook for future research.

2. Molded interconnect devices (MID)

The MID technology features advantages like 3D design freedom, high reliability and reduced manufacturing costs. MID-parts are injection molded thermoplastic parts with integrated three-dimensional electronic circuit traces. The surface of the used thermoplastics can be selectively metallized to generate these circuit traces. This enables the integration and packaging of electronic components. Furthermore electronic functions like antennas, electromagnetic shields or thermal bridges can be realized. The design of the thermoplastic circuit carrier itself fulfills mechanical functions of the part. Mounting and connection functions are feasible as well as environmental protection or heat management. The number of mass-produced MID-applications has increased significantly within the last years. Figure 2 shows two typical MID-parts.

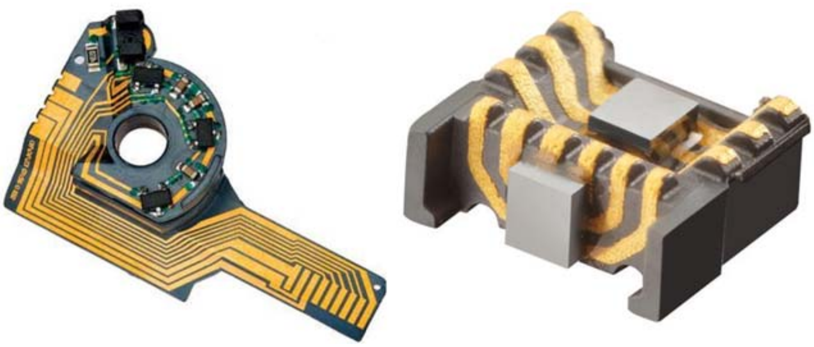


Figure 2. Radar sensor for adaptive cruise control (left) and multiaxial magnetic field sensor (right); Harting Mitronics [Franke et al. 2011]

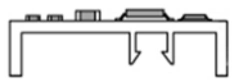
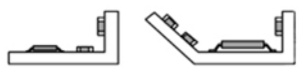
The spatial freedom of scope enables an optimal adjustment of the electronic components according to the operational environment like optical sensors. In particular in applications with limited space new

product concepts can be implemented. This miniaturization is often accompanied by a weight reduction, too.
On manufacturing side the production process chain can be rationalized. The number of parts can be reduced by an integral construction. This affects directly the handling and assembly costs. Installation supports like snap-joints assist the assembly as well as the integrated part reduces defective interfaces within the production.

2.1 Geometrical classification

In general the technology MID offers user-defined three dimensional design opportunities. The freedom of scope is limited though by the different production methods and process steps. These restrictions have to be taken into account during the development process [3-D MID e.V. 2004]. The limitations lead to compromises regarding costs and benefits of the respective part. Planar two dimensional process areas have advantages concerning their processibility. This leads to a standardized geometrical classification (Table1).

Table 1. Geometrical classification of molded interconnect devices [3-D MID e.V. 2004]

Dimension	Attribute	Draft with assembly
2 ½ D	planar process area, 3D-Elements on the opposite side	
	planar process area, 3D-Elements on the same side	
	multiple planar process areas	
n x 2D	multiple planar process areas with different angles	
3D	free-forming surface	

Starting point for the classification is the configuration on a standard circuit board. Its process area and the board itself is just planar and two dimensional. In contrast to this “2 ½ D”-applications use a planar process area on a three dimensional part. On an “n x 2D”-application multiple planar areas are oriented variable to each other. A real three dimensional configuration finally expands its configuration over the full free-forming surface [Rega and Czabanski 2008].

2.2 3D-MID manufacturing

A notable characteristic of the MID technology is the variety of the different production processes (Figure 3). The first three process steps “making interconnect device”, “circuit structuring” and “metallization” are necessary for the creation of the basic part of a MID. The forthcoming processes are relevant for the integrated circuit packaging. The combination of convenient and consistent technologies is called MID process chain [Gausemeier et al. 2010]. Figure 3 shows the general MID process chain, called reference process for MID, and available technologies for manufacturing of MID-parts. Though, some technologies fulfill not only one process step.
The basic MID-part can be created via 1 and 2 component injection molding or film back injection molding. The most important step is the structuring of the circuit. Three technologies are widely used:

- 2C-injection molding: within two consecutive injection molding steps, only once a polymer will be injected that can be metallized in order to realize the circuits.
- Laser structuring: a laser activates certain parts of the thermoplastic device; additive and subtractive process cycles are possible.
- Hot stamping: this procedure combines the structuring and metallization in one step. A hot embossing die presses an already structured metal foil onto the base part.

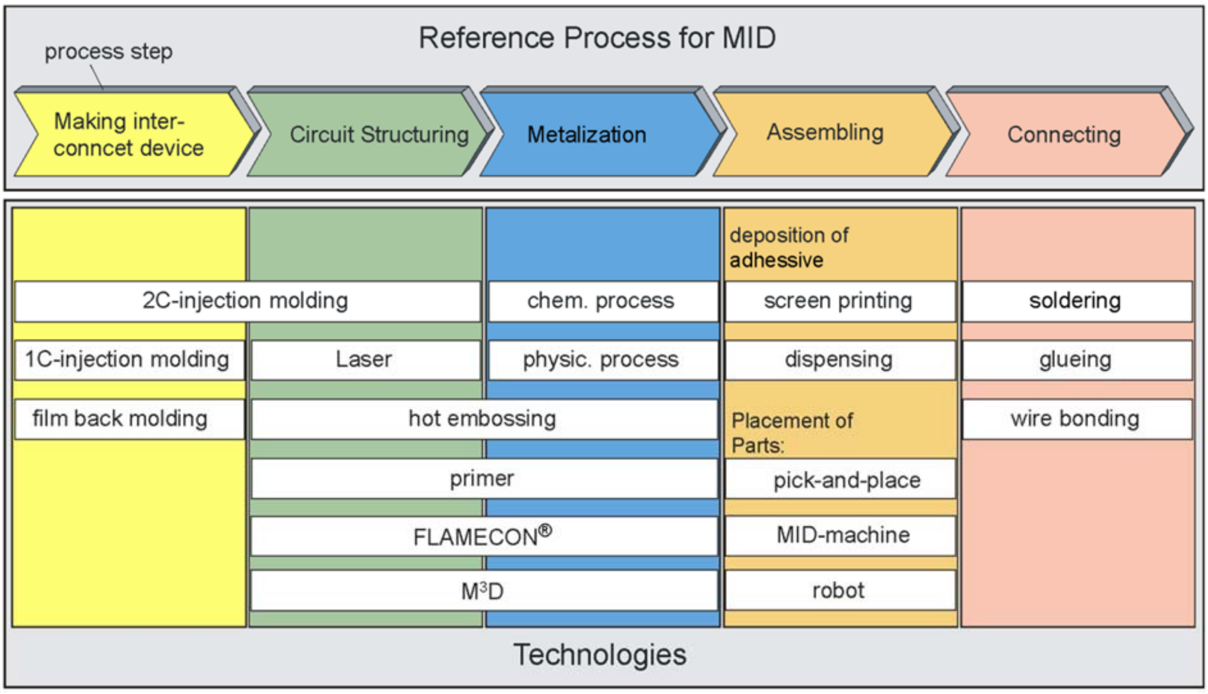


Figure 3. Reference process MID

The next step in the MID reference process is the metallization of the part. This can be realized with chemical, electrochemical or sputtering techniques according to the required layer thickness. The application of electronic components onto the circuit carrier requires different technologies as well. The process can be divided in the following three steps:

- Application of a compound (lead or conducting adhesive)
- Placement of electronic components
- Connecting between electronic components and interconnect devices

The three steps differ in their characteristics according to the selected configuration of the electronic components. Through Hole Devices (THD) require vias in the shape of the thermoplastic carrier whether Surface Mounted Devices (SMD) require wider contact areas and adhesive support. The connecting can be done by wire bonds, lead or contact bumps, as realized in Flip-Chips (FC) for example [Enser and Feldmann 2005], [Hunziger 2005].

2.3 Field of action: development of MID-parts

The design of innovative MID-products requires an interdisciplinary approach. The traditional division of tasks in product development needs to be abandoned for the development of MID-parts. Mechanical engineers, electronics developers, tool designers and manufacturers must closely cooperate already in the early design phase due to emerging interactions and dependencies. The integration of mechanical and electronic function-carriers results in a reinforcement of the interdisciplinary dependencies. The more functions MID-parts integrate, the greater the complexity is. A cross-disciplinary development also has the advantage to prevent problems and changes that often occur later during the development. As a result high correction costs can be avoided [Feldmann and Goth 2008].

Due to the strong dependencies between the product and production process further challenges rise. The possibilities and restrictions in terms of design and functionality depend crucially on the manufacturing process. The developer has the integrative task to pick the convenient technologies, taking into account the product requirements. Already during the conceptual design phase, the product concept is determined by numerous manufacturing restrictions. In addition some design requirements are not realizable by common technologies. An example is the complex spatial arrangement of electronic components, which cannot be realized by conventional processes of two-dimensional assembly techniques. It is important to consider these issues in the development process of innovative products and to detect early possible solutions. Therefore an integrative development of product and production system is necessary.

Process specific application-requirements have to be considered as well. These relate to the thermal and mechanical resistance, chemical resistance, electrical properties and the required reliability of the product for example. For conventional electromechanic components, which have a separate housing and printed circuit board, there are a variety of policies to meet the requirements. These describe the limits of application, process steps or conductance values that support the developers and create a traceable standard. Such guidelines cannot just be transferred from the conventional methods to MID.

Of high relevance is also the identification of innovative MID-product ideas. In general new product concepts need to be make obvious, but also the reengineering of existing applications with MID have to be supported. For the latter case, a method was developed, in which construction catalogues for mechanical and electrical functions are listed as well as respective solutions [Peitz 2007].

Experienced MID-manufacturers rely not only on the knowledge gained from the experience of their employees – they have also developed their own resources; for instance several MID-guidelines exist by now. These document proven solutions and design rules for certain engineering tasks. They allow a manufacturable construction and point out the important aspects of the process chain. However, there is no general guideline for the development of MID-parts. All existing guidelines describe solutions and a procedure for one specific MID manufacturing process. As a result, they can only be used after the manufacturing process was selected by the developers.

Only a few dedicated IT tools have been developed for the design of MID-parts. Tools that support integrated three-dimensional mechanical system and electronics design are available on the market, but rarely used [Franke et al. 2011].

3. Design patterns for the development of MID-products

In order to meet the outlined challenges for the development of MID-parts, we tried to identify and specify design patterns, which describe not only a recurring problem, but also a convenient solution to that problem. Within those design patterns dependencies of the manufacturing processes and especially geometric information have to be stored for an efficient reuse. The patterns shall help the developer to realize the MID-potentials taking the restrictions into account. For this work feasible mechanical and electrical functions as well as restrictions for different MID-manufacturing processes have been defined by analyzing existing MID-applications. Based on this application analysis an MID-specific construction catalogue was acquired, which contains also solution elements for those functions. Furthermore several existing design guidelines have been reviewed to point out restrictions for the used manufacturing processes. The MID-patterns derived from the developed conclusions contain design characteristics, possible product functions and process requirements to facilitate the design process of innovative MID-products.

3.1 Application analysis

There are many MID-applications running in series production. The MID-products point out which MID-process chains are state of the art. We have analysed eleven selected applications and demonstrators form different market segments, taking account of geometrical features, necessary manufacturing processes and restrictions, materials, and mechanical as well as electrical functions. Figure 4 shows some of the analyzed applications. Most of the analysed MID-parts were manufactured by laser direct structuring (LDS), which corresponds to the short process chain as well as the changing flexibility. Mounting of electronic components is mainly done on planar process surfaces, because of challenges with 3D assembly lines.

Figure 4. Motor cycle switch (left, Kromberg & Schubert) solar sensor (middle, Harting), steering-wheel switch (right, TRW) [Franke et al. 2011]

The acquired information was documented in product profiles. A product profile consists of characteristic geometrical features and realized mechanical and electrical functions as well as their solutions. Further the product profile describes characteristics of the manufacturing process. It is important to note that the geometrical feature establishes the relation between geometrical information, mechanical and electrical functions and a common MID-manufacturing process. Figure 5 shows the product profile of a motor cycle switch. The basic characteristics are the different and arbitrary arranged process surfaces for structuring and molding, which requires an automated and flexible 3D assembly.

Product Profile: motor cycle switch (1/2)	
General Data	
Product name	Motor cycle switch
Developer/Manufacturer	Kromberg & Schubert
Material	Ultramid® T 4381 LDS
Mechanical functions	**Solution**
support component	three-dimensional arrangement of the mounted process surfaces
contact assembly group	drill holes to fix the motor cycle switch at the handlebars
transfer power	plug- in connector, snap-on connection
protect from environmental influences	paint coating
mark component	reference points for the packaging processes; bar code
stabilize component	reinforces braces and increased material thickness for increasing the component stiffness

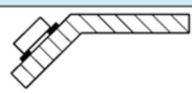
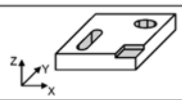
Product Profile: motor cycle switch (2/2)	
Electrical functions	**Solution**
transport electrical energy	conductor track
open/close circuit	switching elements consists of silicon
contact electronic components	SMD-soldering connection
contact with peripheral assembly groups	SMD-plug in connector, press-fit pin
Manufacturing processes	
LPKF-LDS and packaging process: 3D design of process surface	
Packaging process: lead-free soldering process; 3D dispenser system; SMD-components	
Structuring: automatic and flexible 3D assembly	
Geometrical features	
Defined alignment	
Handling positions	

Figure 5. Product profile of the motor cycle switch

In addition to the geometrical features the solutions for the MID-functions are a result of the application analysis. It is noticeable that several functions occur repeatedly; but differ in their solutions. The mechanical function *contact with peripheral neighbour group* for instance can be realized through a plug-in connector or a snap-on connector. It is obvious to summarize the available solution variants for defined product functions in a construction catalogue. Hence we have extended an existing preliminary MID-construction catalogue from Peitz [2007]. The construction catalogue consists of two parts. The first part provides solutions for electrical MID-functions. The second part

provides solutions for mechanical functions (Figure 6). The catalogue lists the MID functions in the rows, while the solutions are arranged in the columns. The catalogue is completed trough short descriptions of the solutions, taking design guidelines into account.
The MID construction catalogue contains the most used and most important solutions for MID-functions. Hence the catalogue supports the developers search for appropriate solutions. What is lacking are design restrictions imposed by the MID-manufacturing processes, especially considering the whole MID-process chain and the appropriate combination of solutions to a specific design task.

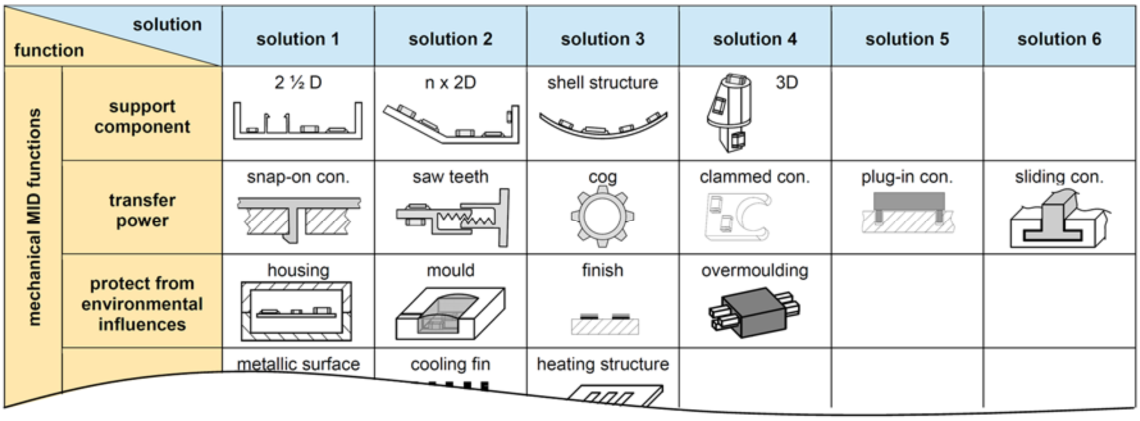


Figure 6. Extend construction catalogue for mechanical MID-functions (cut-out)

3.2 Design requirements through manufacturing processes

There are strong dependencies between the MID-product and the MID-manufacturing process. The requirements of the MID-manufacturing processes limit the solution space for the design, because they represent restrictions for the product. In purpose to identify the restrictions for product design MID design guidelines were reviewed. For this reason the whole MID-process chain was considered (cp. Figure 3). For the process stages we have summarized the restrictions for each MID-manufacturing process. For purpose of a design guideline the requirements are outlined concisely.
At the 2-component injection molding, for instance, the layout of the conductor track depends on the injection molding itself. Requirements on the conductor track layout design have to be taking into account already at this process stage. Nevertheless, the existing design guidelines focus only on the design of the MID-part. The influences of manufacturing parameters (e.g. temperature or pressure during injection) are not considered, although they affect the characteristics of the MID-part (e.g. adhesion of metal coating). Exemplarily restrictions to product design for 2-component injection molding are possible conductor track width or conductor track spacing’s, which both result from the pressure during the second injection.
As a result design guidelines are available, which have to be considered while using corresponding MID-manufacturing processes. These guidelines have to be allocated to geometrical features, so that the developer gets an integrative description of MID-functions, possible solutions and manufacturing restrictions.

3.3 MID patterns

For the developer it is very difficult to harmonize product requirements and manufacturing restrictions as well as the dependencies between mechanical and electrical functions. A contributory factor here is that the knowledge on different MID-manufacturing processes and its restrictions is distributed over the whole MID-process chain. Therefore MID-patterns are necessary, which describe design features and regarding manufacturing restrictions in an integrative way.
A MID-pattern depicts a solution concept for the design of an innovative MID-part. It illustrates integrative design concepts for product requirements as well as mechanical and electrical functions to be fulfilled and considers the restrictions of the manufacturing processes. The specification of a MID pattern is structured in five aspects in order to cover the development of MID-parts (Figure 7).

Characteristics: This part describes the characteristics of the pattern. Because of the requirements of the product and the restrictions of the MID-manufacturing process we distinguish two sub-categories of this aspect: characteristics of the product and of the manufacturing process. Examples for relevant characteristics of the product are *geometrical classification* and *product requirements*. The aspect geometrical classification describes the shape of the process surface (e.g. 2 ½ D or 3D). With regard to the development task the product requirements presents those requirements, which can be fulfilled through the pattern (e.g. adapt components to external assembly groups or adjust components defined). Characteristics of the manufacturing processes are *device manufacturing*, *materials*, *packaging technology*, and *systems engineering for 3D assembly*. The aspect device manufacturing names possible device manufacturing processes for structuring and metallization. If there is a particularity with materials, it is mentioned with the aspect materials. The aspect packaging technology describes possible construction concepts for mounting electronic components on the metallised surface. With the aspect systems engineering for 3D assembly particularly geometric characteristics should be specified.

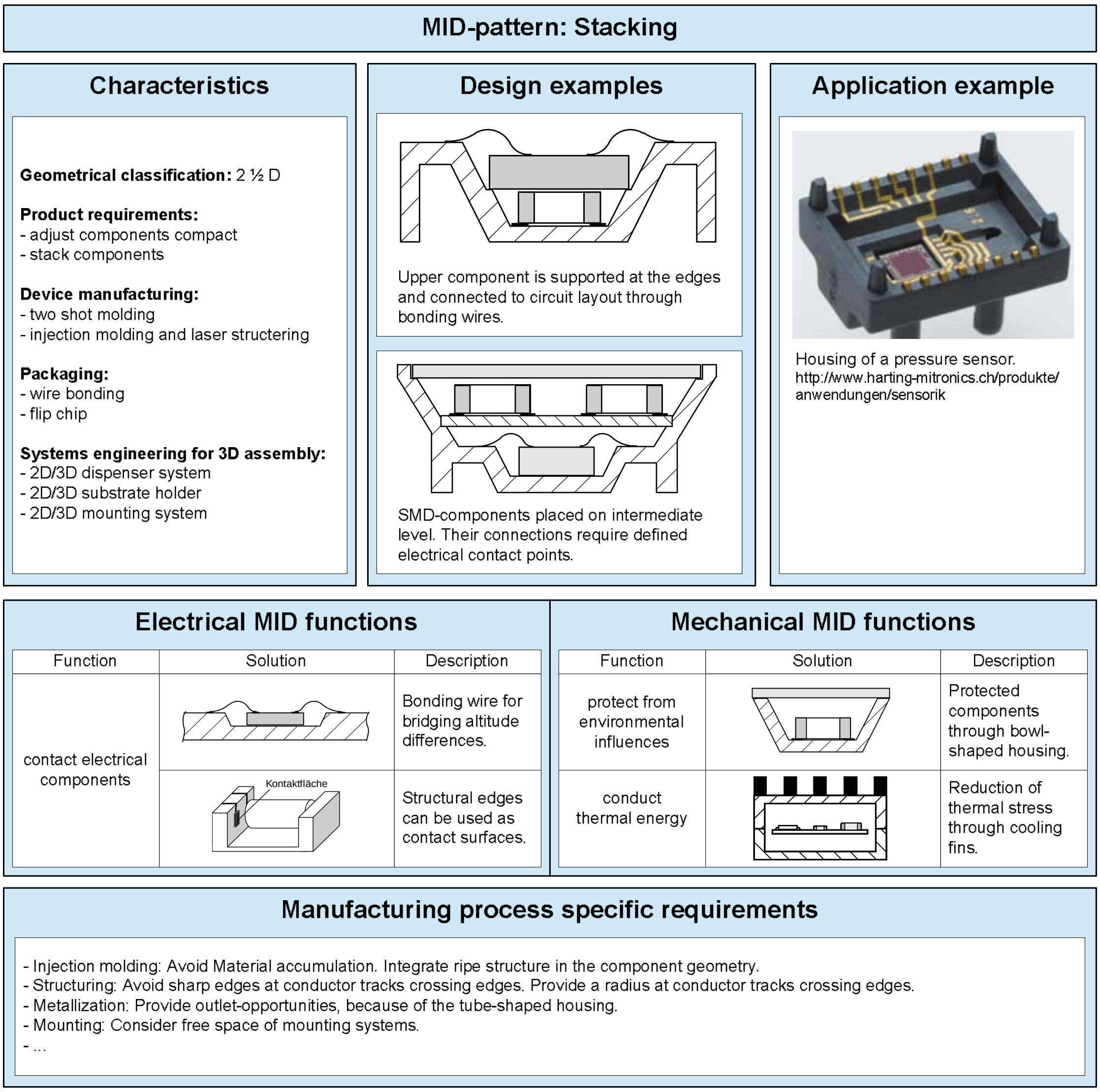


Figure 7. Aspects of MID pattern for the design of MID-parts

Functions: This aspect contains all those mechanical and electrical MID-functions that can be realized by the MID-pattern. Moreover various design options for the MID-functions are shown. The solutions are proposals for fulfilling the MID-functions in context of the MID-pattern. Hence this aspect shows single solutions for the pattern, which the developer can combine in order to find the best solution for the specific application.

Design examples: This aspect demonstrates the exemplary combination of the solutions for the MID-functions in context of the MID-pattern. In addition, the examples demonstrate suitable designs for manufacturing.

Manufacturing restrictions: The restrictions through the manufacturing processes take into account restrictions of single manufacturing processes as well as of the combination of different processes over the whole MID process chain. It is mentioned which design requirements und guidelines have to be considered. The developer gets valuable design requirements for the realization of the MID-part through the pattern.

Application example: A pattern has to adapt to a specific design task. Examples, which clarify the successful usage of the pattern have to be presented.

MID-patterns describe a design challenge as well as a convenient solution. It consolidates all necessary information for the design of an innovative MID-part, considering restrictions of the MID-manufacturing processes. Hence the patterns support the developer in handling the complex dependencies of product requirements and manufacturing restrictions. Thereby the MID-patterns contribute to rise development quality and to reduce development time.

4. Application example

In the following we apply the MID-patterns for the design of a sensor platform. The platform should be used in an assembly group for the detection of hand gestures for the control of computer systems. Therefore acceleration sensors have to be placed orthogonal to each other. Further requirements are limited construction space and the integration of flat standard battery.

The development of the MID sensor platform starts with the identification of the necessary functions, the platform has to perform. In the next step the developer has to assign known system elements to implement those functions. During this step functions that could be realized by MID have to be identified. MID-functions are those, which can be fulfilled by MID-solutions (e.g. carry components, conduct electricity, protect form environmental influences; cp. Figure 6). Then solutions have to be found for the mechanical and electrical MID-functions. For this purpose the developer searches for convenient MID-patterns, which also fulfil the product and manufacturing requirements. In this case the patterns *alignment*, *fastening*, *adaption*, *cavity*, and *conductor track layout* were used:

- Alignment: The acceleration sensors were placed on orthogonal and planar surfaces. The high accuracy of the injection molding facilitates the defined alignment of the sensors.
- Fastening: The sensor platform is fastened in the neighbor assembly through grooves offset by 90 degrees. This enables an exactly defined position of the platform relative to the neighbor assembly.
- Adaption/Cavity: The external shape of the MID-platform is exactly adapted to the shape of the neighbor assembly. This allows the optimal use of the available construction space.
- Conductor track layout: The conductor track layout is designed according to the requirements of the LDS process. For example the walls of the cavities are titled by 30 degrees.

Figure 8 shows the CAD-Modell of the sensor platform, which is the result of the usage of those MID-patterns.

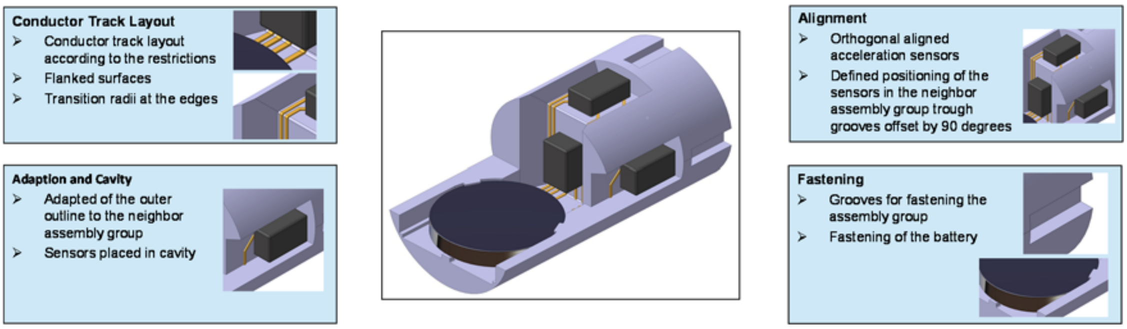


Figure 8. Concept of the sensor platform based on MID-patterns

5. Conclusion and outlook

The MID technology offers great potential for innovative products. However, it lacks of market success due to several barriers. Most of these barriers concern the development process: The complexity of MID-products due to their domain-spanning nature and occurring interactions between product and production system. These interactions have to be considered during the design process. Since the design process of MID-products is the key aspect to successfully bring MID-ideas into market; the demand to support the design process is obvious. In order to realize these potentials and to meet the challenges for the development of MID-parts, we have specified MID-patterns. These patterns describe design features for product requirements and MID-manufacturing restrictions in an integrative manner. Altogether we have identified seven general MID-patterns so far. They contain design characteristics, possible product functions and process restrictions. For the identification of the patterns we have analyzed existing successful MID-applications. We also demonstrated briefly how those patterns support the development of a new sensor platform.

Future work will focus on the identification and specification of further MID-patterns. This concerns in particular the aspects and characteristics of the manufacturing requirements and may result in an adjustment of the structure of the MID-patterns. In addition, we will integrate the use of the patterns in an overall design methodology for the development of mechatronic integrated devices. For this purpose we are looking forward to develop a computer support for the pattern-based design of MID-parts.

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