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DESIGN FOR FUNCTIONAL INTEGRATED SHAPE MEMORY ALLOY SYSTEMS

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1. Introduction

Actuators based on shape memory alloys (SMAs) are developed to be used only in special applications. Therefore solutions based on SMAs in general, cannot be transferred to other tasks. The focussing only on the development for special applications has two important disadvantages. Firstly the effort and costs reach a high level due to the individual development and secondly the development of complex SMA-actuators turns out to be an insuperable barrier for many companies. Reasons are the complex characteristics and the missing simulation- and design tools. In order to make statements about the functions and durability of the SMA-component extensive tests need to be performed.
As a result there is significant interest in providing standardized SMA-actuator systems with complex and also variable functions. Construction kit systems allow transferability to different areas of application and they also lead to a reduction of variants. Using standardized components is an interesting opportunity to reduce the risk of individual development and the effort for single applications effectively. However the increased system complexity of conventional construction kit systems is a problem (additional functions required, e.g. the mechanical and electrical coupling of the modules). Apart from the conventional form of a construction kit system there is the possibility of a variable SMA-actuator system generated by the configuration of a single SMA-component. The existing and unique potential of SMAs for function integration and therefore standardization can be used to its full extent.
The aim of this paper is to provide methods and the knowledge to support the development process of such SMA-structures. The development of these methods is based on the analysis of designs of smart structures and potentials for function integration were also derived. Based on the results, instructions for the conception of integrated SMA-structures were created in order to find feasible solutions. The most important factor is the achievable level of function integration.

2. Fundamentals

Figure 1 gives an overview of the characteristics, describing the SMA-actuation elements. These characteristics must be considered for the development of SMA-elements. Generally SMA-actuators can be considered as mechatronic systems leading to special requirements during the development process. Here mechatronics are understood as both a technical product type and an interdisciplinary engineering science which uses system techniques to integrate mechanics, electronics and information technology and further required technological areas [Czichos 2006]. The definition shows that development processes that lead to a mechatronical product have to follow an integrated approach to keep the desired synergies even at process level. For this reason the VDI-guidelines 2206 were published, containing guidelines for the development of mechatronic systems. These guidelines include important aspects of interdisciplinary processes and heterogeneous product structures.

Developments of SMA-based products should be accomplished in accordance with those guidelines. The development of SMA-structures without the consideration of electronically or IT-supported components requires an extension and/or adaption of the mechatronic process model.

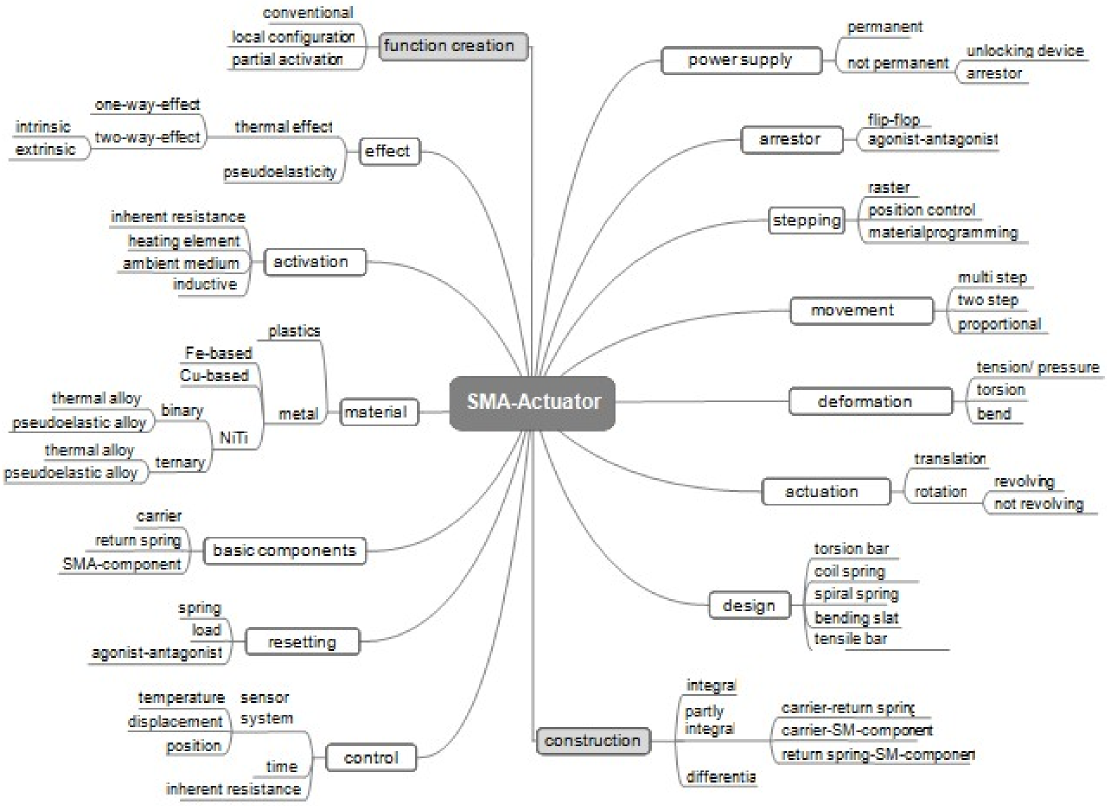


Figure 1. Characteristics of actuation elements

3. Extension of mechatronical process model

3.1 General view

The use of SMA-components in mechatronical systems leads to new aspects which were not considered in the previous process model [VDI-Richtlinie 2206]. Unfortunately there is no methodical support of the development process for function integration. In fact there are only approaches aiming for an integration of functional materials but there is no consideration of SMA-components from a mechatronical point of view. In this case the classification of the SMA-technology into the solution space of mechatronic systems is relevant. The solution space of mechatronical systems describes the different views which are necessary during the concept phase. This is important to get an integrated and interdisciplinary description of the system to be developed. The consideration can be subdivided into system level, module level and sub-system level. The special feature during the development of mechatronical systems is the constant change from a detailed to a superior level and vice versa in order to detect the alternating connections between the sub-systems. Moreover a change is caused to the abstraction level. The aim of the development is to provide precise solutions based on abstract problems. An alternative is to find a solution using system technical treatment to get from a precise problem to an increased abstraction level. The third treatment level is subdivided into different model levels which are necessary to find a solution concept. It includes the correlation of function, effect and design [Jansen 2006].

In order to integrate SMAs into a mechatronical design, the different views of the solution space must be applied to SMA-components. The development of the function structure does not require an extension of the previous procedure. In this case the use of predefined function modules simplifies the

procedure. The basic functions that an actuator must have were identified in a patent analysis. “must-” “can-“ and auxiliary functions can be differentiated. A suitable function structure is given in figure 2.
In case of the function structure, the SMA-element is activated by its inherent resistance via electric energy. The displayed functional blocks show the basic functions of electrical activated actuators, whereas the actuators dissipate the electric energy via thermal energy into mechanical energy. When the actuator consists only of these functional blocks, it performs a translatory or rotatory movement (only performed once because the actuator has no resetting element) depending on the design. When a resetting element is needed the functional block “dissipate” is added, where the mechanical energy is dissipated into a potential one. The energy is re-dissipated (resilience) into mechanical energy, shown by the feedback of the block. Then the actuator works on the principle of the extrinsic two-way-effect. There is also the possibility to store the potential energy in form of a mechanical flip-flop-mechanism. With these requirements a further function block “store” must be integrated into the function structure. When a rotary motion should be performed in a contracting actuator element instead of a translatory movement, it is necessary to transform the contraction of the SMA-elements into rotation by means of constructive design features. Figure 2 shows this transformation inside the function structure using the function block “convert”. A transformation of mechanical energy must be taken into consideration where adjustment travels or actuating forces do not meet the standards of the SMA-elements. In case of actuation of the actuator there is also the option to install a position measurement system for control oriented reasons. This option is shown with the function block “detect”. When the actuator requires all function blocks there is a complex actuator system which is able to work autarkic because of the sensor technology. The patent analysis also made obvious that the functions “store energy” and “detect position” are underrepresented in patented applications.

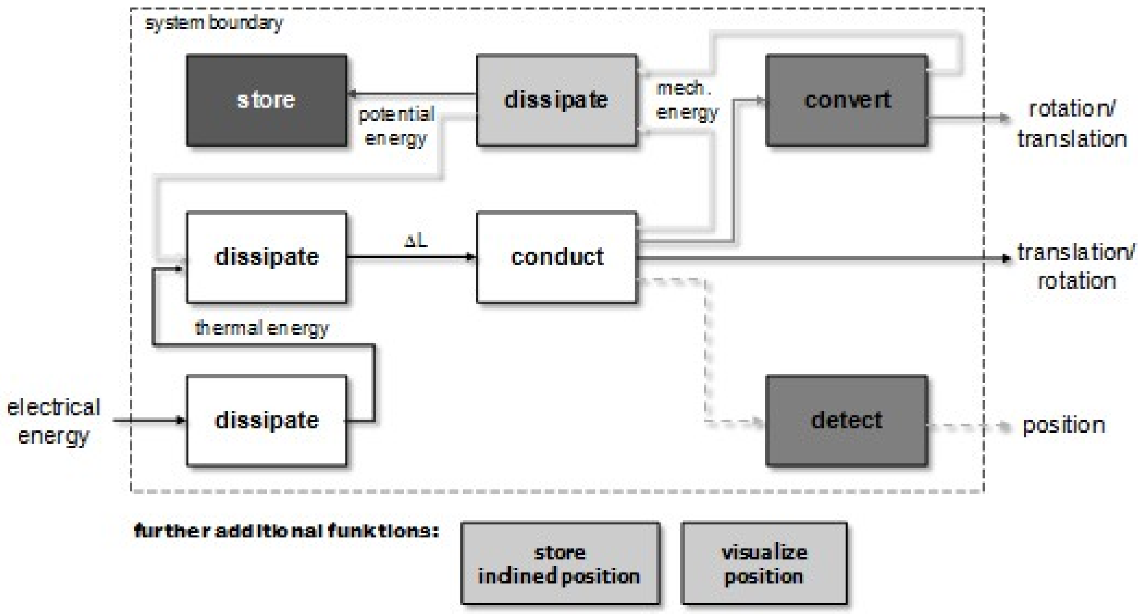


Figure 2. General function structure at electric activation

3.2 Partitioning of SMA-components

Observing the structure of an SMA-actuator the implementation of a new term is necessary. The possible and locally restricted function giving via local configuration or partial activation requires the structuring beneath the component level. In this context partial activation means the heating of a defined region of an SMA-component by the corresponding transformation temperatures. As a result the SMA-effect is temporary and locally restricted. In case of local configuration a permanent and locally restricted effect is achieved by structuring- or heat treatment methods [Langbein 2009]. Moreover, we were able to demonstrate that the tension plateau and the transformation temperatures could be changed locally. Figure 3 shows the possibility to influence the mechanical properties of a

NiTi-SMA-wire by heat treatment. Besides, the sensitivity and hence the problems of annealing processes becomes apparent. An example for a local annealed SMA-sheet is shown in figure 4. Due to the different transformation temperatures the sheet shows a step behaviour by activation of the thermal shape memory effect.

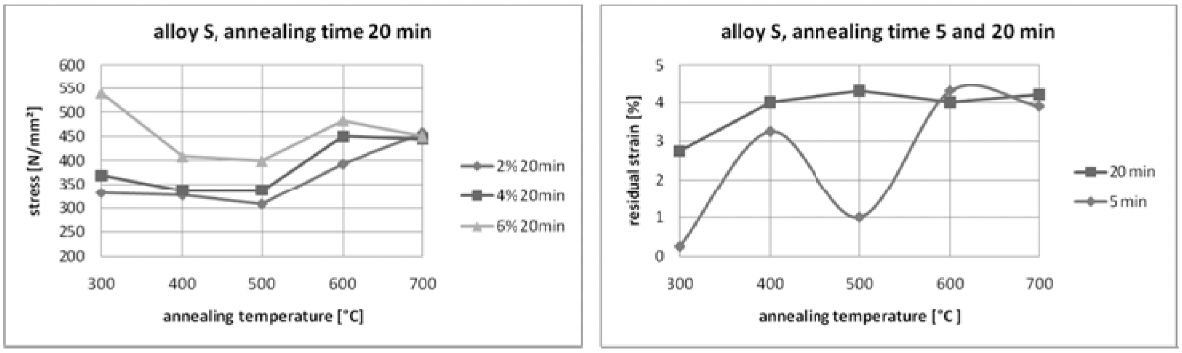


Figure 3. (a) Distribution of stress of the 20 min annealed samples and (b) residual strains of 5 min and 20 min annealed samples with a high-nickel alloy (alloy S)

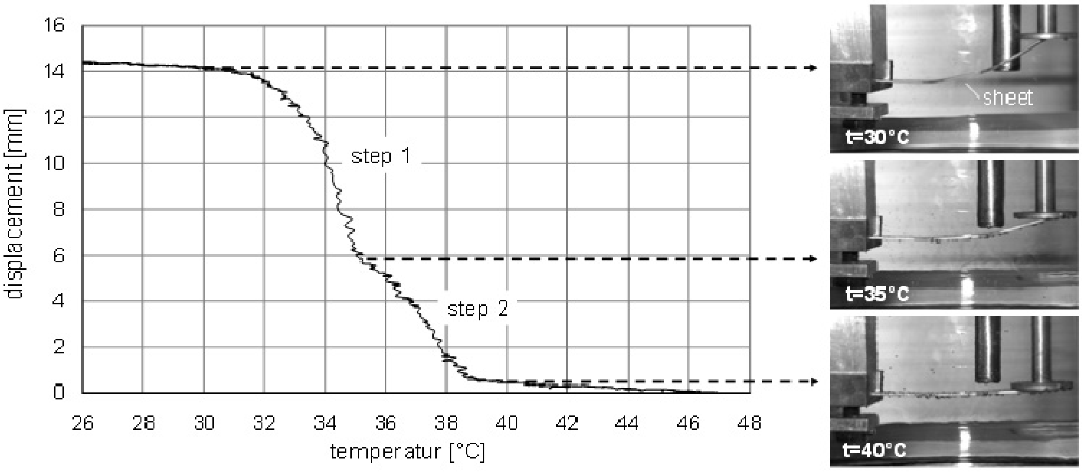


Figure 4. Step-actuator based on locally configured sheet metals of the alloy S

The structuring level of such components is called *partition*. Accordingly a conventional SMA-component has only one partition and therefore it is identical with the component itself. Due to local configuration or partial activation the component is further subdivided into at least two more partitions. The exact number depends on the spatial arrangement of the effect. Figure 5 depicts the meaning of the term partition.

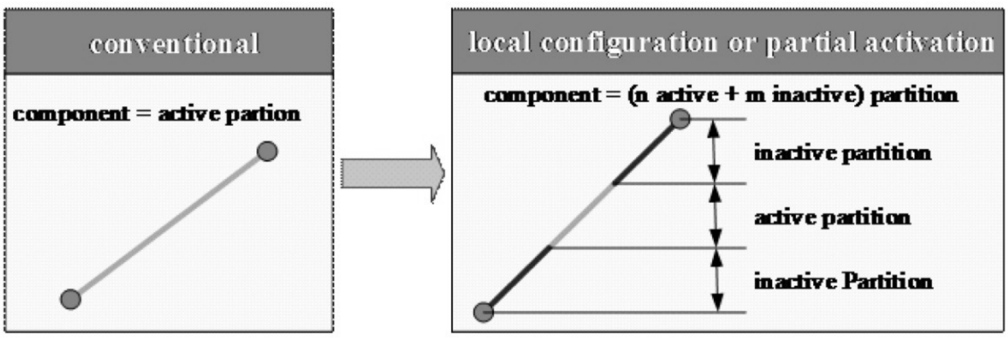


Figure 5. Partitioning of SMA-components

In order to use the full integration potential of SMA-actuators two requirements are needed. Firstly the transition from the differential construction to the integral construction has to be considered systematically. Secondly the use of local configuration and/or partial activation has to be investigated contrary to the conventional function giving. In this way SMA-actuators can be generated which show a high level of function integration.

3.3 Integration method

Figure 6 shows the design space for the approach of integration of SMA-based systems. Looking in horizontal direction, barriers between the different designs ‘differential’, ‘semi-integral’ and ‘integral’ can be identified and have to be resolved. This can be achieved in two steps. At first, different functionalities have to be partially integrated. The partial integration can cover different systems related to the number of the integrated functions. During the transgression of the barrier towards partial integration the interfaces between system elements on the functional level and the design structure level have to be examined. This examination is needed to evaluate if integration is possible at all. If the partial integration has reached a high level a detailed evaluation of the potential regarding full and/or partial integration can be carried out. At the process of integration (i.e. crossing a barrier) real interfaces between system elements are transformed into partition interfaces.

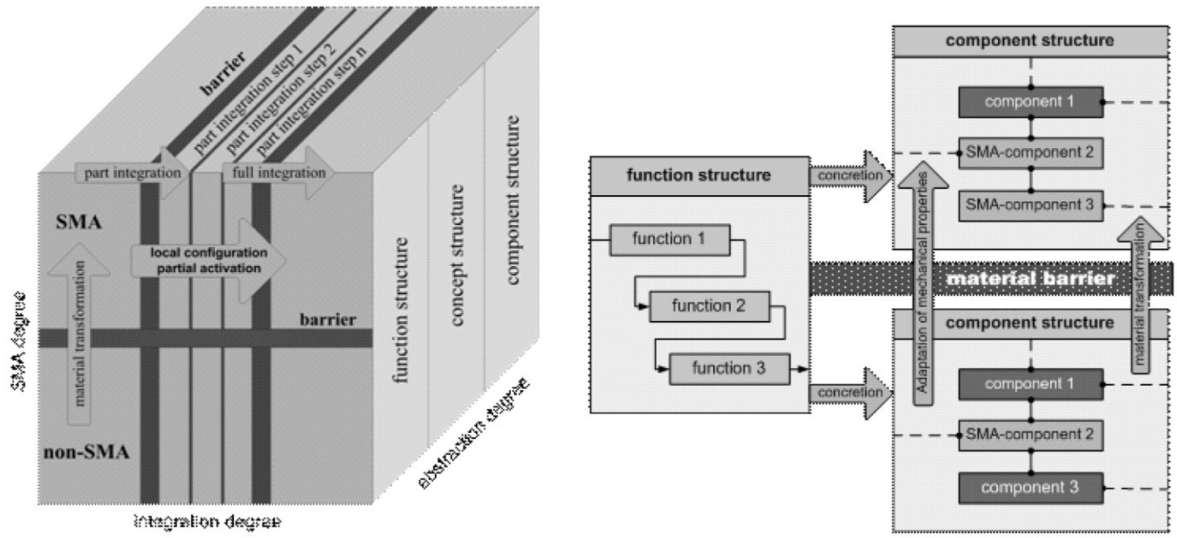


Figure 6. Design space for the integration of SMA-based systems

Crossing the barriers in vertical direction is another case. While crossing the barriers the transformation from non-SMA-elements into SMA-elements occurs. This transformation is required for the function integration based on the local configuration and/or partial activation. In order to create a totally integrated SMA-actuator structure this barrier has to be passed at least once. The position referring to the axis of integration level is not important at all.

The distinction of part and total integration is made by the resulting design structure of the entire system. If only one component remains while crossing the interface level or barrier the system can be characterized as ‘totally integrated’. The integration is performed by an arrangement of partial functions to one module and its functionality is realized by one component only.

Besides figure 6 depicts the transformation of components made of conventional material into an SMA-element. Here the transformation occurs at the design structure level. The design structure level results from a specification of the functional level. The functional structure itself is still intact after the transformation is finished. During material transformation it is important to consider any changes related to the form and production methods of the components. In this case design rules and production methods of SMAs have to be integrated into this transformation. The function giving methods of the local configuration and the partial activation are used if an integration of the SMA-components is performed after the transformation of the component material.

3.4 Interface analysis

Figure 7 and figure 8 depict the functional structures of SMA-actuators previously mentioned in this abstract. The basic functions of an SMA-actuator system are shown as well.

Figure 7 shows the system with external activation as already described in Fig. 2. Such systems are complex considering additional required controlling efforts and have a high number of interfaces which lead to a high potential of component integration. The analysis of the interfaces between the functions referring to the interface matrix by Erixon [Erixon 1998] is given in this figure, parallel to the function analysis. An evaluation of the integration level of these functions is described as well. In the left triangular matrix the interfaces are characterized according to their energetic and geometric relations as well as in terms of signal quality. The arrows show the direction of the corresponding flow. Below the diagonal of the right matrix an evaluation of the integration potential is performed. Above the diagonal of the right matrix information regarding the applicable integration method is given. In this context, structure integration means the integration of components by a change of the active principle and their shape. In most cases this is achieved in combination with a change of material and also the production method. The integration by function giving methods includes the combination of SMA-components and SMA-effects in one component. In order to generate such a component a material transformation from non-SMA-components to SMA-components has to be included eventually (vertical direction in the design space). Integration by multi-functionality means that a component can basically accomplish different functions. Examples for such basic functions can be identified as the heating of SMA-elements by their electric inherent resistance and the controlling of SMA-elements using their load line. Using this matrix all the desired functions of an actuator system to be developed can be integrated based on the position within the design space.

Figure 8 shows an activated actuator system by an ambient medium. The main difference regarding the functional structure shown in Fig. 2 is that the partial functions „store potential energy“ and „detect position“ can be omitted in this case. Contrary to the electrical activation, which aims for a second and currentless operation mode, keeping the initiated position is guaranteed by the temperature of the medium surrounding the actuator. The ambient medium itself inherits all tasks regarding electricity and controlling. As a result, these systems consist of fewer components and show the potential of total integration. The illustration and the evaluation of the interfaces are carried out equivalent to the electrical activated systems.

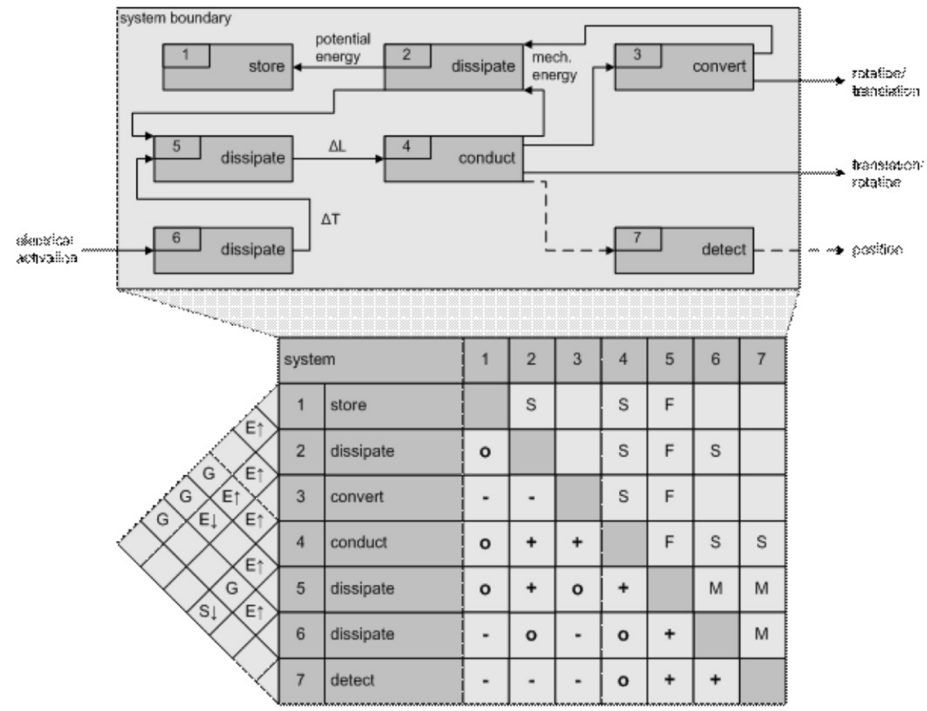
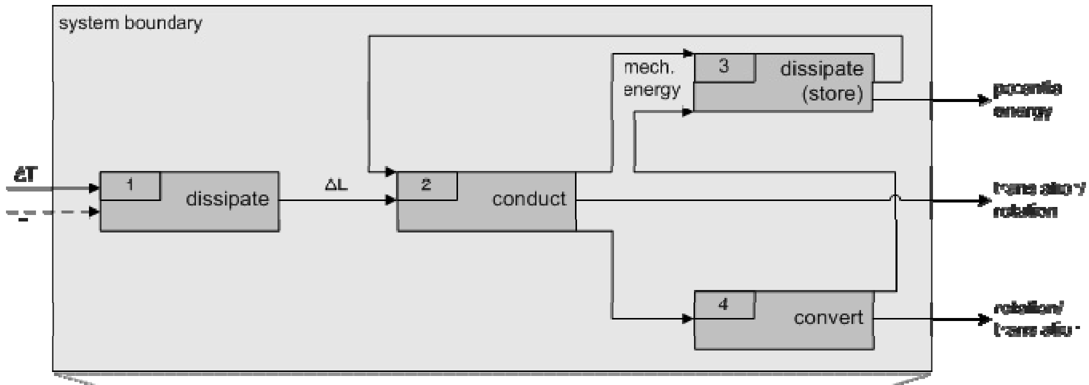
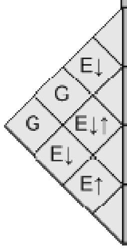


Figure 7. Interface analysis of electrical activated SMA-actuator systems





system		1	2	3	4
1	dissipate		F	F	F
2	conduct	+		S	S
3	dissipate	+	+		
4	convert	o	+	-	

legend					
characterization of interfaces		valuation		method	
G	geometrical correlation	+	good realizable	S	structural integration
E	energetic correlation	o	generally realizable	F	integration by local kcnfiguration/ partial activation
S	signaling correlation	-	not realizable	M	integration by multi-functionality

Figure 8. Interface analysis of SMA-actuator systems activated by the ambient medium

3.5 Evaluation with respect to a diamond actuator

As an example, a multi-functional applicable and functional integrated regulating actuator is described [Langbein 2008]. This actuator (figure 9) only consists of three main components, the functional integrated plastic carrier, the SMA-element and a heating element. The plastic carrier itself inherits the task of a carrier and/or base structure as well as the tasks of travel transformation and resetting the SMA-element. These tasks can be achieved by providing a defined reset force of its solid body hinges. As a result, the actuator reaches a partial integrated status.

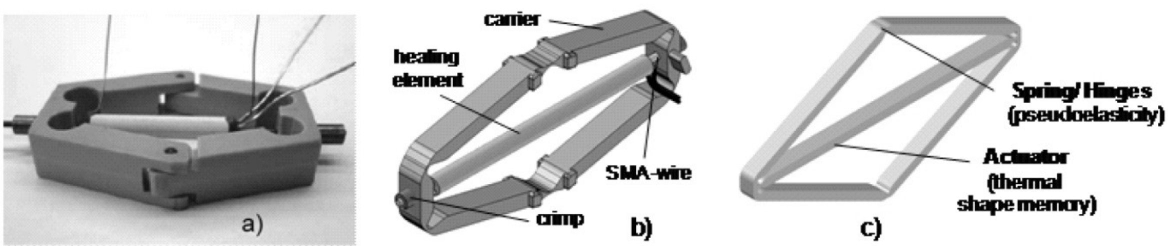


Figure 9. Diamond actuator with SMA-drive a) realized actuator b) CAD-schematic of the actuator c) monolithic designed diamond actuator

Figure 10 shows the movements of the diamond actuator (refer to Fig. 8) within the design space. Thus it appears that the aim of total integration can be achieved following different approaches. On the one hand there is the possibility to integrate all non-SMA-components in horizontal direction (1 over 2 to 3). After that, a transfer into an SMA-component using vertical direction (3 to 6) is performed. Finally, the SMA-component can be integrated with an SMA-actuator element (6 to 7). On the other hand there is the possibility to start with the transformation of the non-SMA-components into SMA-components (1 to 4) followed by a stepwise integration until reaching total integration (4 to 7). In between, further possibilities exist where material transformation is performed at early phases of partial integration.

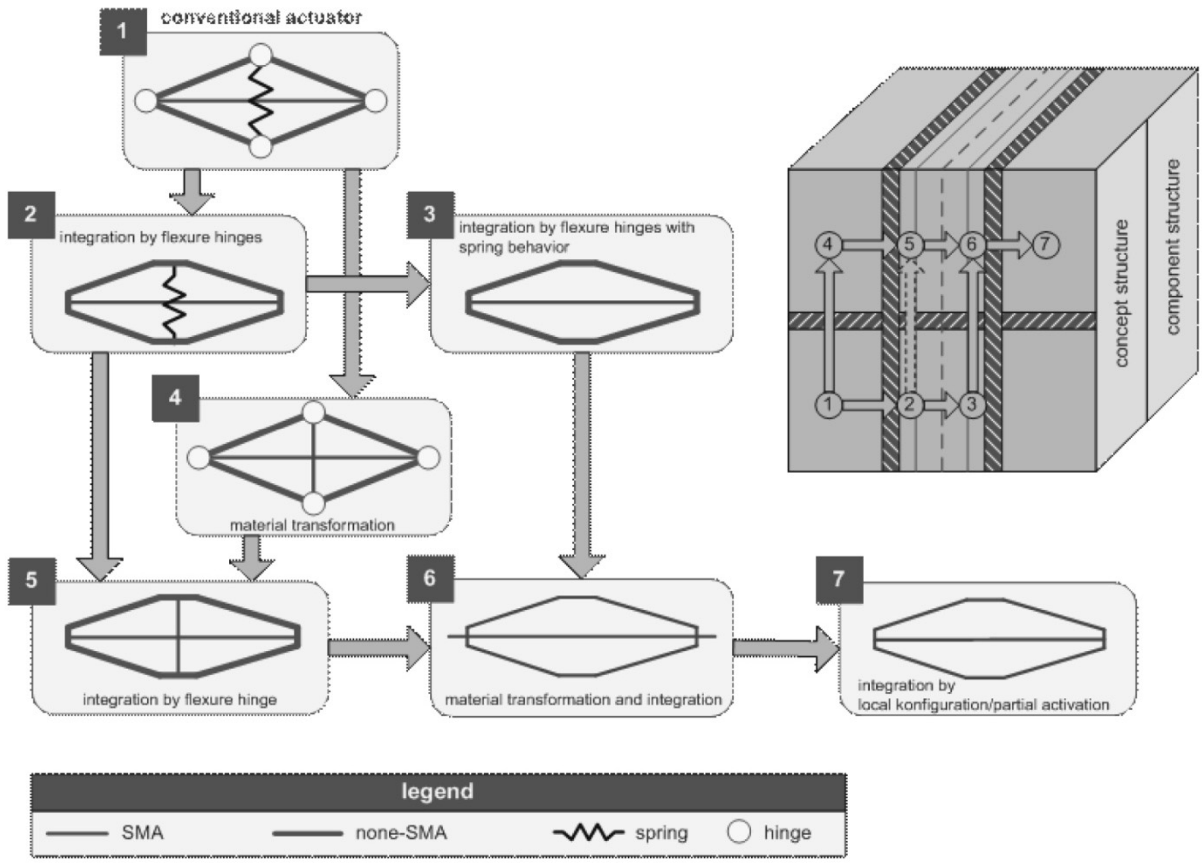


Figure 10. Evolution of the diamond actuator within the design space

The transfer from the conventional design to the monolithic design is explained by means of a hinge according to figure 11. In this figure the different approaches of total integration are shown. One approach describes the transformation of an external interface into an internal interface by transgression of the interface level in horizontal direction. In detail this means that a conventional hinge can be transformed into a solid body and/or material bonded hinge. After that the material transformation into an SMA is performed. A second approach describes the conversion of the non-SMA-components into SMA-components. However, these components are still connected by a conventional hinge. In the next step the integration is carried out which leads to a partitioning of the emerging SMA-component. In case of an individual hinge there is the possibility to use pseudo elastic material which has been generated at the hinge connection by structuring methods. A further possibility is given by the local configuration of the hinge area towards the pseudo elastic effect. The remaining partitions show either a pseudo elastic effect or no pseudo elastic effect and are used as structure material.

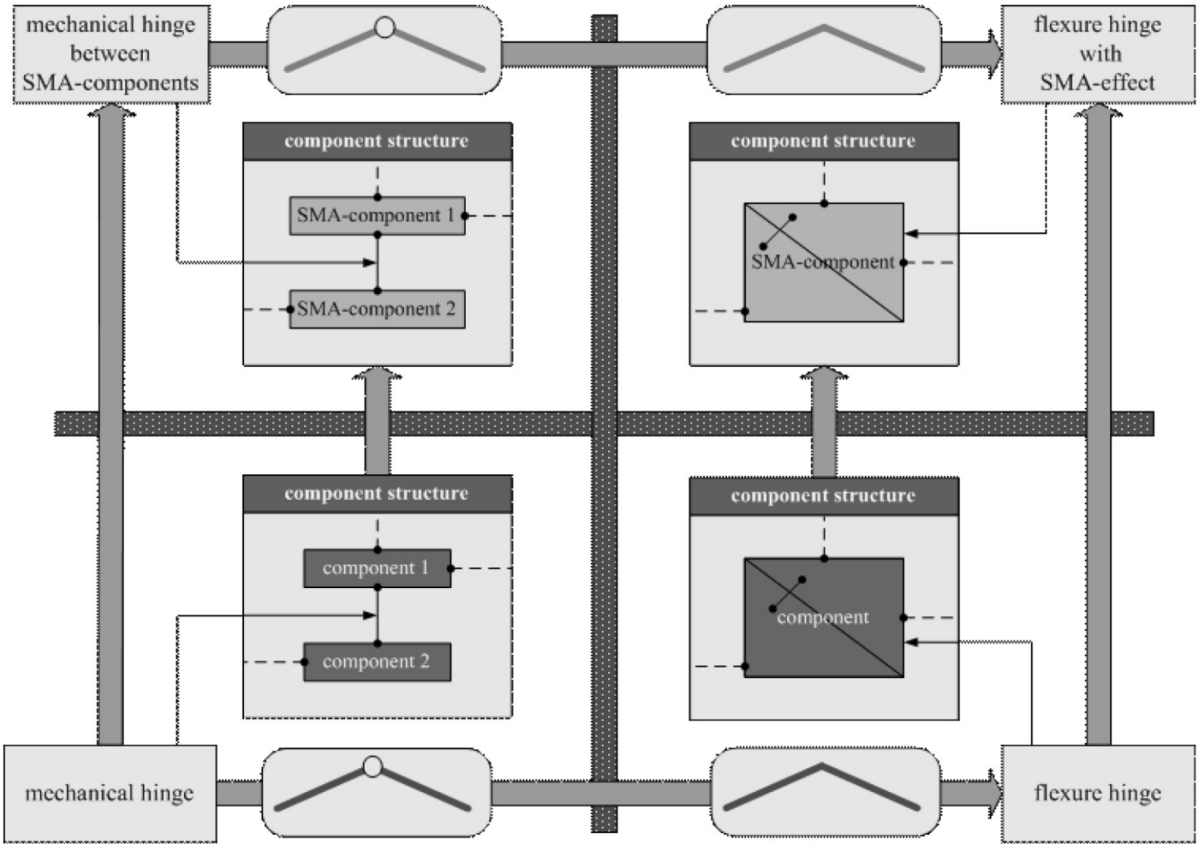


Figure 11. Design evolution according to a hinge

Finally, figure 12 displays the integration of a diamond actuator according to an interface matrix. The described interfaces of two hinges with an integration potential are good examples. The interfaces exist referring to hinge G2 and G4 and are marked. The aim is to resolute all the external interfaces. These interfaces have a geometric and energetic origin as the SMA-wire acts as a converter and its mechanical output is transmitted by the hinge and the rods. The integration of the hinges is performed in two steps. At first the external interfaces are transformed into internal interfaces using solid body hinges. After that the material is transformed which results in the development of pseudo elastic SMA-hinges. In order to reach a total integration of the component the remaining hinges G1 and G3 have to be integrated, too.

4. Conclusions

The study at the one hand has demonstrated that SMAs have a very distinctive standardization- and integration potential. The reasons for these potentials are distinctive features of SMAs (compared to other materials) such as adjusting different effect specifications and therefore different functions in one component. Thereby two methods can be used for local generation of SMA-effects and/or smart actuator structures.

Besides, a method was developed to support development processes together with multi-functional SMA-components. The developed method was based on structural analysis as well as the releases of interfaces between the system components. A special emphasis was put on the support of the function integration and therefore the realization of multi-functional structures. The method was evaluated by a prototype actuator resulted from the specification of a partially integrated structure.

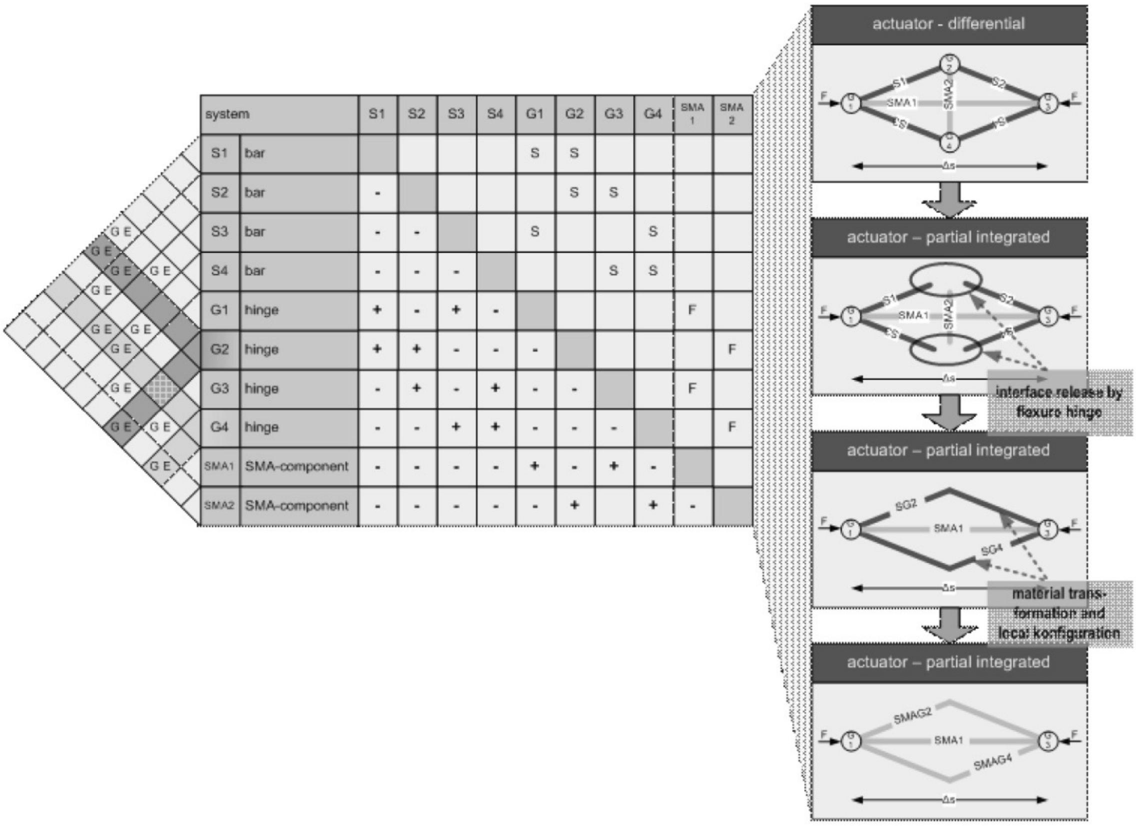


Figure 12. Integration by using an interface matrix

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