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Potential Analysis of Smart Materials and Methodical Approach developing Adaptive Designs using Shape Memory Alloys

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Abstract

High-tech materials and new processes enable innovative concepts in the field of product development. Smart materials can generate new and efficient products through controllable properties. These materials are increasingly investigated in research studies. One typical example are shape memory alloys. Their special property of remembering the original form after deformation leads to the development of lighter, more efficient, more energy-efficient and innovative solutions as well as products. In the following, therefore, shape memory alloys are investigated especially in the area of product development. Special focus is laid on the possible applications within adaptive designs.

Smart materials are becoming more important in research, but actual use has not increased to the same extent. Reasons are, for example, high material and development costs and lack of development methods. The following study focuses on the material Nitinol (nickel-titanium alloy). There are already numerous publications on the behavior of the martensitic and austenitic conditions and on position control. Nevertheless, there is still a lack of concrete fields of application, especially in the field of industrial design engineering. Therefore, the specific use of Nitinol and an increase in the range of application contain great potential.

Nitinol is currently, generally speaking, restricted to applications in the medical and aerospace industries. In order to extend its use and application to other areas, a standardization of the shape memory actuators, application-specific integration and design possibilities as well as development and design methods would be necessary. For example, the use of shape memory alloys in vehicle contexts could allow for weight reduction, aerodynamic improvement, and increased user comfort and ergonomics. So, the use of shape memory alloys could potentially initialize completely new applications and areas of application.

The present study examines areas of application of smart materials in general, focusing on shape memory alloys, in particular Nitinol. The result is an overview matrix of already used and applicated smart materials in order to detect further research potential, to enable the transfer of already used technologies and to define new fields of application. The matrix is categorized into different smart materials and their application within the fields of ergonomics, design and

technology. This method for potential estimation thus shows new areas of application and leads to links with already established areas of application. This will enable a transfer of already explored or proven technologies to new topics.
Particularly promising is an application related to motor vehicles. Growing demands on innovative vehicles, for example regarding a higher safety, comfort and functionality, lead to an increased total mass. Therefore, leightweight, adjustable components offer great potential. In particular, door handles, aerodynamic elements and interfaces within the interior design contain potential for the use and application of shape memory alloys.
The results of the developed matrix in combination with the application areas in motor vehicles are elaborated using the example of a door handle, realized as a prototype. Based on this proof of concept, first approaches to a method for the design and integration of Nitinol are presented.

Keywords: Design methods, adaptive systems and structures, smart materials, shape memory alloys, user centered design, vehicle exterior design

1 Introduction

In future design processes, adaptive structures and systems will play a key role, since passive structures are optimally designed for only one operating point and cover only a small range of users. To implement those multifunctional structures and systems, smart materials are quickly gaining attention, as their properties can be adapted in a controlled way by external stimuli.
Thus, they realize high functionality in simplified structures leading to new, innovative and efficient product designs. Instead of separating function and structure, smart materials integrate functionality into the material's structure.
Within those materials shape memory alloys (SMAs) are increasingly examined. Comprising two stable solid phases (high temperature phase: austenite and low temperature phase: martensite) these alloys undergo a transformation from one phase to another by following particular paths in the stress-temperature space. This ability to return to a previously defined shape or size occurs when subjected to the appropriate thermal procedure. In a certain temperature range, SMAs can be strained up to 8 % and are still able to return to their previous shape. Nevertheless, SMAs exhibit nonlinear, hysteretic behavior (Janocha, 2007).
The main characteristics of SMAs application are a high energy density, the simplicity of their mechanical design and a minimum number of moving parts, a low operating frequency, high strains and high stress. Most promising are Ni-Ti alloys, which offer the best combination of properties, especially in terms of the amount of work output per material volume and a high amount of recoverable strain. Shape memory alloys can be used in a wide range of applications: lightweight actuators design, noiseless actuation, aerospace and naval to surgical instruments, medical implants and fixtures. They are resistant to corrosion and biocompatible.
The following study comprises the application potential of smart materials in general, SMAs in particular and especially focuses on Ni-Ti alloys. This is interesting for products, which combine ergonomic and individual requirements with lightweight and package requirements focusing on the design appearance. The vehicle is a typical product containing such parameters. Therefore, the study discusses problems and advantages of SMAs in specific automotive applications and provides first approaches to implementation.

2 Adaptive Structures and Systems

Adaptive structures and systems are "adaptable to changing external conditions by using at least one multifunctional element. Common to all is the integration of sensors and / or actuators in structural components. Furthermore, control units and processor extend functionality and intelligence. Another similarity is the purpose to generate a structure or system with enhanced performance but avoiding the increase of mass. This will lead to new opportunities in lightweight construction." (Hein, 2017)

Smart materials are applied as multifunctional elements in adaptive structures and systems. Adaptive structures and systems are mainly applied within the fields of vibration and noise control, shape and position control and monitoring for impact supervision. However, there are numerous advantages to be transferred to new applications. Adaptive structures and systems aim at improving the operational lifetime, supporting lightweight design, increasing safety, enhancing precision, increasing ergonomics and comfort, reducing maintenance, enhancing functionality and offering new design possibilities. Besides these advantages, there exist also problems and challenges. Those can be solved given the right possibilities.

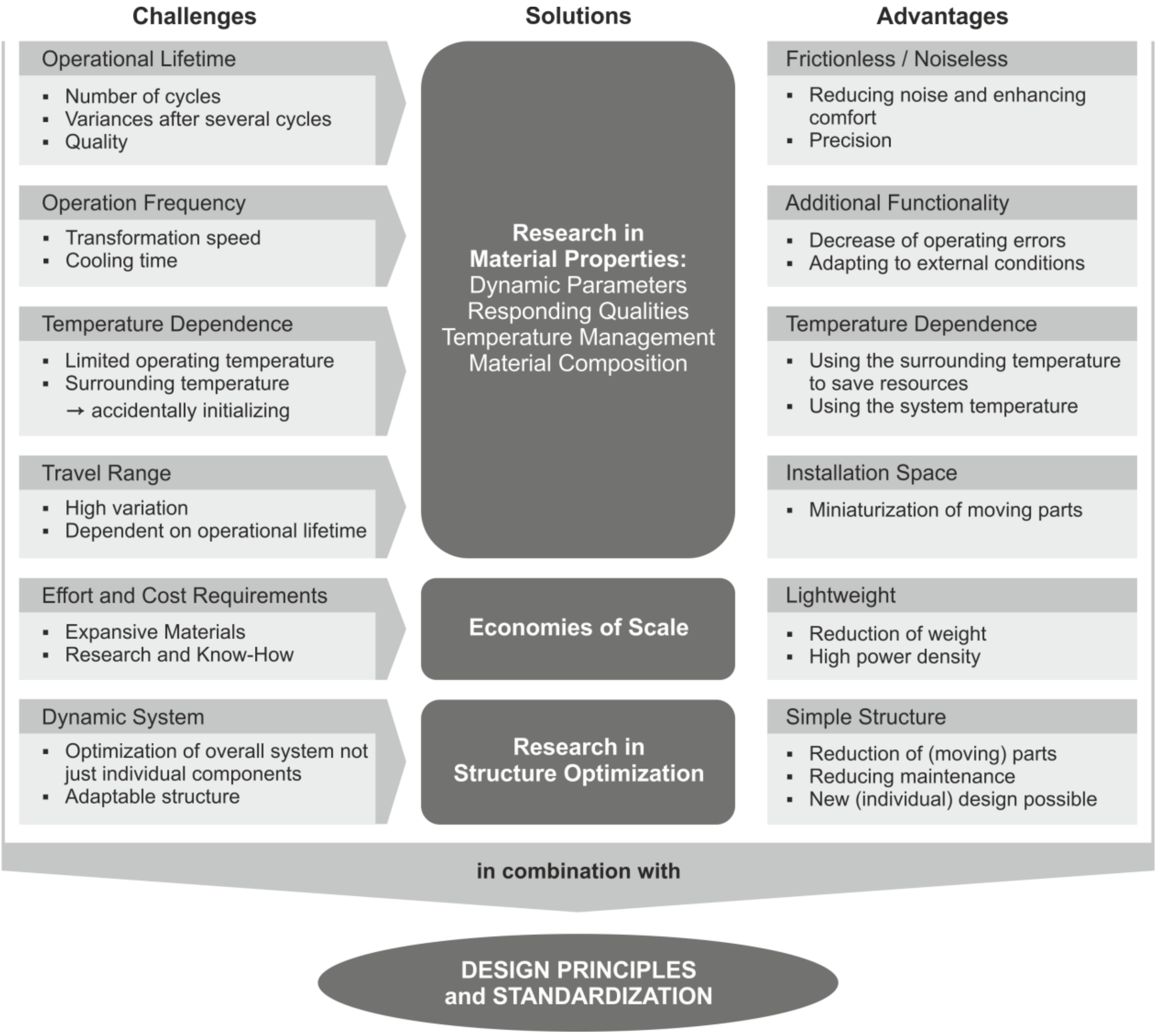

Figure 1. Research focus depending on challenges and advantages of smart material applications.

3 Smart Materials

The term smart materials is often used and often replaced by the terms intelligent or adaptive. This problem is already long known and investigated. An appropriate definition was provided by Rogers in 1988. He defined smart materials and smart systems as "[a] system or a material which has built-in or intrinsic sensor/s, actuator/s and control mechanism/s whereby it is capable of sensing a stimulus, responding to it in a predetermined manner and extent, in a short

/ appropriate time and reverting to its original state as soon as the stimulus is removed” (Rogers 1988, S. 4). This characterization is still up to date and does not need any adaption. Nevertheless, it does not include a classification of smart materials. There exist many classifications of smart materials regarding their activation / actuation, strain and stress, phase (solid, liquid, fluid), change of properties (shape, color, phase) or physical effect, though none of those includes the applications of smart materials.
The following study focuses on solid phase materials with applications already modeled in research, design and development.

3.1 Applications of Smart Materials

There are already numerous publications on the properties, the control and the optimization of smart materials. Nevertheless, there is still a lack of concrete fields of application, especially in the field of industrial design engineering. However, it is highly important to gather and systemize the different applications to benefit from existing investigations. For further classification three main fields of applications for adaptive structures and systems (Hein, 2017) are identified, categorized and proved by examples in research, design and development (table 1). Within the field of ergonomics existing applications focus on comfort and haptic interfaces. The sector of technology is most widely studied. Experience exists within eight main fields: safety / emergency, (lightweight) structures, aerodynamics, fluid / hydro dynamics, locking devices, microsystems, resources and health devices. Regarding the design, smart materials are utilized to promote individualization or to adapt the shape for aesthetic reasons.

Table 1. Examples for applications with smart materials.

Ergonomics	Comfort	noise and vibration, damping, acoustic emission
	Haptic Interfaces	tactile displays, touchscreens, portable force and feedback devices, switches with tactile device
Technology	Safety / Emergency	safety clutches, emergency brakes, smoke detectors, safety valves, bonnet lifting
	(Lightweight) Structures	self-deployable and self-folding structures, adaptive wings, solar systems, deformable mirrors, smart skins
	Aerodynamics	adaptive wings, adaptive spoilers, smart skins, active controls, piezo fans
	Fluid / Hydro Dynamics	valves, pumps, loudspeakers, motors
	Locking Devices	flaps, grippers, switches, terminal connections
	Microsystems	microvalves, microgrippers, micro actuators, microrobotics, microelectronics
	Resources	self-healing, energy harvesting, heat engines, lagging, generators
	Health Devices	stents, minimal invasive surgery, soft catheters, splints, artificial muscles
Design	Individuality	fashion, spectacle frames, adaptive logos and signs
	Shape	fashion, curtains, facades

The matrix shown in table 2 correlates materials and applications in order to reveal the existing experience. It is thereby possible to detect potential applications, to derive new applications from existing applications, to transfer applications to different materials (horizontal shift), to correlate applications of one area for optimization and to transfer advantages to different applications (vertical shift).

The matrix only contains material systems with already existing applications in research, design and development. Extensive research investigated the field of applications in view of existing experience as well as the number and type of different applications. The degrees of fulfillment (circles) do not only consider the number of different applications, but also the quality of the implemented applications.
Analyzing table 2 it can be stated that SMAs are already greatly researched and applicated. Nevertheless, there is still great potential regarding the fields of ergonomics and design. In the field of technology safety / emergency, lightweight structures, aerodynamics and resources should be advanced and conveyed to new applications within those fields. It is recommended to focus on already investigated materials using promising findings to derive new applications.

Table 2. Applications with smart materials in comparison.

Experience	Materials	SMAs	Magnetic SMAs	Shape Memory Polymers	Dielectric	Piezo	Elektro-strictive	Magneto-strictive
Ergonomics	Comfort	●◐○	○○○	◐○○	◐○○	●●○	◐○○	●○○
	Haptic Interfaces	●○○	○○○	◐○○	◐○○	●○○	◐○○	◐○○
Technology	Safety / Emergency	●◐○	○○○	●○○	◐○○	●●○	○○○	○○○
	(Lightweight) Structures	●●○	○○○	●○○	●○○	●◐○	◐○○	○○○
	Aerodynamics	●●◐	◐○○	◐○○	◐○○	●◐○	◐○○	◐○○
	Fluid / Hydro Dynamics	●●◐	◐○○	◐○○	●○○	●●○	●○○	●◐○
	Locking Devices	●●◐	◐○○	●○○	◐○○	●●○	●○○	◐○○
	Microsystems	●●◐	●◐○	●◐○	●◐○	●●●	●○○	●◐○
	Resources	●◐○	●○○	●◐○	●◐○	●●○	●○○	○○○
	Health Devices	●●●	◐○○	●●●	●◐○	◐○○	◐○○	◐○○
Design	Individuality	●○○	○○○	○○○	◐○○	○○○	○○○	○○○
	Shape	●○○	○○○	●○○	○○○	◐○○	◐○○	○○○

3.2 Properties of smart materials

In order to select the appropriate material for the desired application it is necessary to detect and compare the important properties of smart materials (table 3). Important characteristics are those, which have direct and visible influence on the application and the user, who is in direct contact with the application.
The time needed to transform the material is essential. It states how often a transformation can be reproduced within a given time. The process or transformation temperature is significant not only with regard to the applied system, but also to the user. As the human-machine-interaction is an important topic within the design process, it is necessary to develop safe systems. Strain and stress mostly define the possible applications and the design process. It is essential to consider the number of cycles and therefore the operational lifetime of a material. While designing an adaptive system a possible replacement of the material must be taken into consideration.
As each of the listed material classes contains different materials, the stated properties differ. Table 3 summarizes the average to best performances of the materials in order to give an overview of possible performances of the materials. However, research has shown that even

within publications on the same materials, properties differ and as material research is still conducted, the materials are continuously developed further.

Table 3. Properties of smart materials in comparison. (Behl, 2007), (Bucht, 2015), (Carpi, 2008), (Duerig, 1990), (Elspass, 1998), (Janocha, 2010), (Köhnlein, 2000), (Liu, 2007), (Olabi, 2008).

	SMAs (Ni-Ti)	Magnetic SMAs (Ni-Mn-Ga)	Shape Memory Polymers	Dielectric (acrylics & silicones)	Piezo	Electro-striktive	Magneto-striktive
Process / Transf. Temp. (°C)	-50 ... 110	> 65	-20 ... 50	-10 ... 90 -100 ... 260	165 ... 300	> 10 ... 80	> 380
Strain (%)	> 8	> 10	> 200	> 380 > 120	0,1	0,1 ... 0,25	0,2
Stress (N/mm²)	150 ... 200	5	2 ... 3	8,2 3,0	press.: 600 tension: 80	similar to piezo	press.: > 880 tension: > 40
Operating frequency (Hz)	0 ... 20	0 ... $x*10^3$	< 1 s ... sev. min	> 50000	> $100*10^3$	> 50000	10000
Number of cycles (10^6)	> 1	> 200	N/A	> 10	> 10^3	N/A	N/A
Typical travel range (mm)	5 - 30	N/A	N/A	N/A	0,1 ... 1	~ 0,15	0,05 ... 0,2
Voltage (V/m)	Low	-	-	$440*10^6$ $350*10^6$	$1*10^6$ 10^2 ... 10^3 V	> $2*10^6$ 0 ... 300 V	-

Analyzing table 3 it can be stated that SMAs do not exceed the other material classes in all categories, but at the same time do not contain great disadvantages like high voltages (dielectrics, piezo, electrostrictive), high weight due to necessary equipment (magnetostrictive: weight and size of magnetic coil), disturbance due to magnetic field (magnetostrictive), minimal strain (piezo, electrostrictive, magnetostrictive), low possible stress (magnetic SMAs, shape memory polymers).
Therefore, SMAs are interesting and promising materials regarding a broad application. It is possible to not only applicate them to specific tasks but to those, combining many requirements.

3.3 Analysis of potential fields of application

By comparing the different materials and their properties to the "experience matrix", it is possible to assign the materials to matching fields of application (figure 3). Promising are, above all, areas of application that combine the three main fields ergonomics, technology and design. It is thereby possible to exploit the whole potential smart materials offer. By means of the application matrix, general fields of applications are derived. As stated above, especially shape memory alloys comprise this feature. Above all, electric tools, vehicles and wearables are promising fields for broad applications of shape memory alloys.
Regarding the properties and possible fields of applications the main advantages of smart materials and shape memory alloys in general are the installation space (volume), the lightweight design and the complexity (number of parts / degree of order).

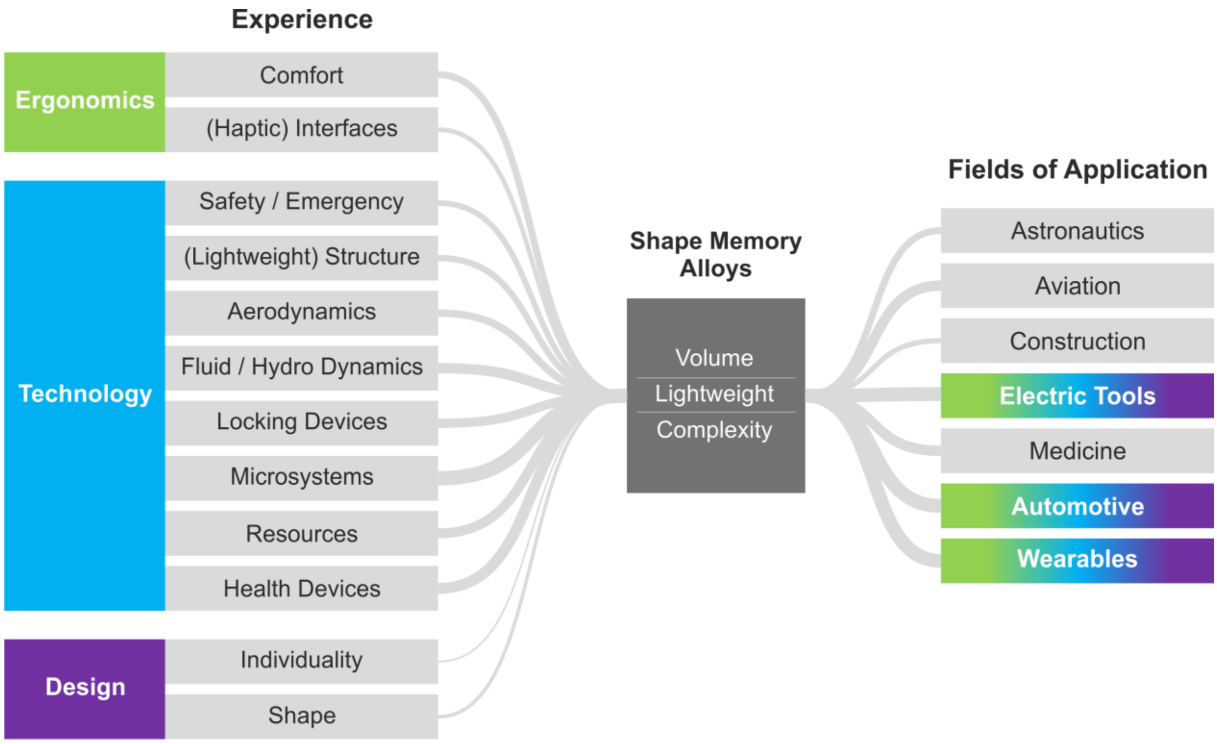

Figure 3. Fields of application for shape memory alloys considering the three main fields ergonomics, technology and design.

4 Shape memory alloys

Shape memory alloys are able to convert into a previously imprinted shape through means of thermal and electrical activation. This effect relies on the phase transformation within the material from low temperature martensite to high temperature austenite. This transformation is possible even under high applied loads, whereas during the cooling process the absence of stress is important.
Characteristic temperatures are the martensite start (M_s), martensite finish (M_f), austenite start (A_s) and austenite finish temperature (A_f). There is a hysteresis between A_s to A_f and M_s to M_f, as forward and reverse transformation occur at different temperatures. The shape strongly depends on the thermomechanical treatment (Janocha, 2007).
There are three different shape memory effects (Langbein, 2013). The one-way shape memory effect needs an external force to deform the shape within the martensitic phase. The material reconverts to its original shape upon heating (austenite). No shape change emerges when the element is cooled again. The two-way shape memory effect describes both shapes, a high and a low temperature shape. The material must be trained to undergo the two-way effect. Upon cooling, a very low force can be exerted. Pseudoelasticity (superelasticity) emerges due to stress induced martensitic phase transitions. In a certain temperature range, the transitions from austenite into martensite occur if a critical stress is reached. The component is deformed at high temperature (in the austenitic state). The pseudoelastic effect therefore requires no temperature change and the material returns even after high deformations back into the original state (Langbein, 2013).
The small dimension and low weight of shape memory actuators allow realizing compact and powerful actuators. Shape memory systems usually contain fewer parts than conventional systems. This reduction also leads to an enhancement of the reliability of the generated products. The compact design allows an implementation in small installation space.

4.1 SMA applications

As stated above, the area of motor vehicles is particularly promising. The mobility of a vehicle combined with the conservation of resources demands lightweight design. The complexity of a car should be reduced if possible. There exist many moving parts, often implemented with electric actuators. As the vehicle directly affects the user, aesthetic design and high comfort are important. In addition, the desire for individualization is increasing.
As an example, the use of SMAs in vehicle contexts could allow for weight reduction, aerodynamic improvement, and increased user comfort and ergonomics. It could be possible for the use of SMAs to initialize completely new applications and areas of application. There are interesting applications in the fields of ergonomics, technology and design. In particular, door handles, aerodynamic elements and interfaces within the interior design contain potential for use and application of SMAs.
Figure 4 depicts the potential applications of SMAs within vehicles. As the sector of technology has already been broadly investigated, the focus of this study lays on elements combining the fields of ergonomics, technology and design.

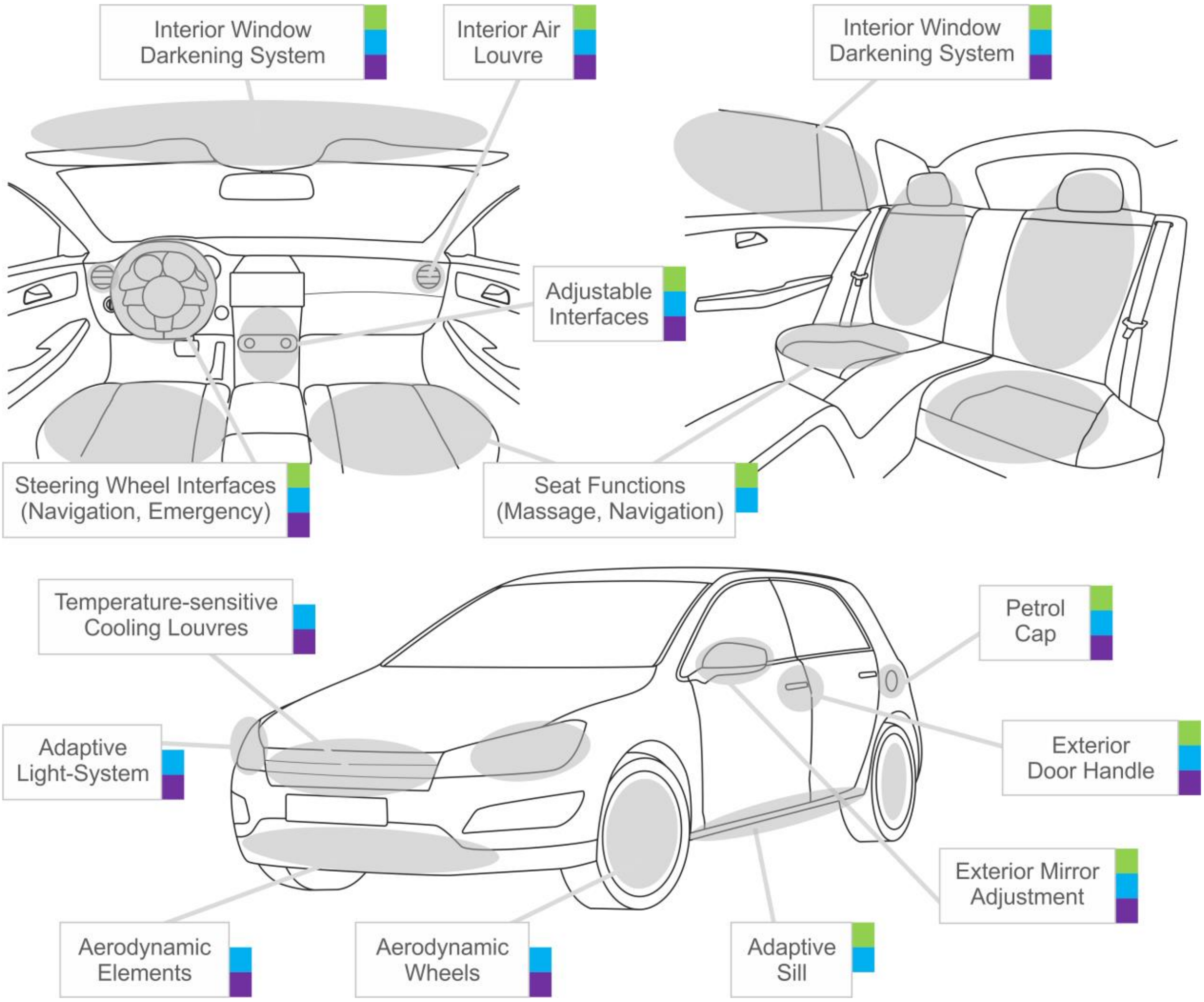

Figure 4. Examples of potential vehicle applications.

Further interesting examples are providing the fields of electric tools and wearables. Possible applications are handholds of electric tools (haptic feedback, emergency feedback), handholds in general (navigation, haptic feedback, emergency feedback), human-machine interfaces (control devices), accessories like smartwatches or jewelry (navigation, haptic feedback, emergency feedback) and transfer of information in clothes.

4.2 SMA prototype: vehicle handle

A conventional door handle has disadvantages with respect to flow characteristics and design features of a vehicle. Especially the handle’s shape creates turbulence and offers limitations in the design process of the vehicle door. The door handle is an archetypal design detail within the vehicle design, which utilizes the great potential of SMAs. It contributes to aerodynamics, there is only a small installation space, the user needs to operate it and there are different users. An adaptive door handle can reduce these disadvantages as it adapts to surrounding conditions.
Vehicle door: The vehicle door must absorb the axial forces of the wire as well as a fixed bearing for one of the two wire ends. The return spring is also attached to the vehicle door.
Door handle: The door handle must be easily deformable so that it can be shortened as the wire changes its shape. The door handle is made by 3D printing with polyamide. The profile of the door handle is weakened by notches that support bending. Furthermore, the profile is in terms of shape and size to match the handle of a conventional door handle.
Shape memory actuator: A Flexinol wire is used as SMA. Flexinol is a Ni-Ti alloy manufactured by Dynalloy, Inc. (Dynalloy, Inc., 2018). By energizing, it shortens its length, which leads to a bend of the door handle. Because an even bending over the entire cross section should be realized several actuators are needed. To design the electrical circuit as easy as possible a wire is used and passed through the profile three times. Guide rollers prevent damage to the wire due to kinking. The use of wires is due to the high availability and a high dimensional range. The element is designed with a return spring.
Actuation: The actuation is carried out by a push-button. This type of activation is similar to the actual operation by unlocking with a radio remote key.
Resetting: The resetting is executed by a steel spring. As soon as the wire is no longer energized and cools again, the spring force leads to a stretch back to its original state.
Control unit: An Arduino Mega is used as a microprocessor. The signal of the button serves as an input signal. Then the SMA will be energized for several seconds. After that, the power is turned off and the wire cools down.
Electrical circuit: The electrical circuit includes the board, the button, the SMA, a transistor, as well as several resistors.

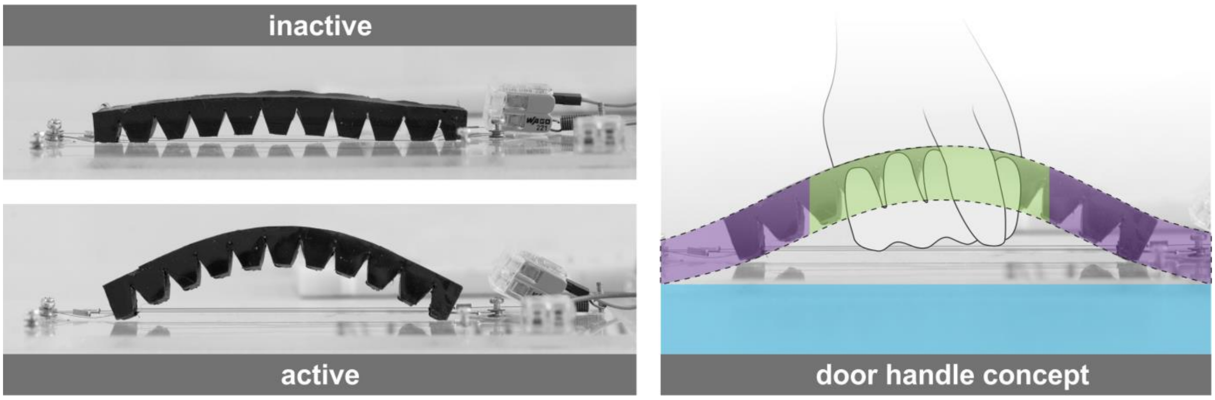

Figure 5. SMA prototype: vehicle handle.

5 Design findings for Ni-Ti human-machine interfaces based on the prototype experiences

Based on the experiences of the prototype, design findings are derived to design Ni-Ti human machine interfaces. Summarizing the findings of this paper, a scheme is developed (figure 6) to design Ni-Ti human-machine interfaces. The scheme is composed of four main elements: external conditions, constraints, design of the adaptive system and the users. Each element interferes with the others through different links and interactions.

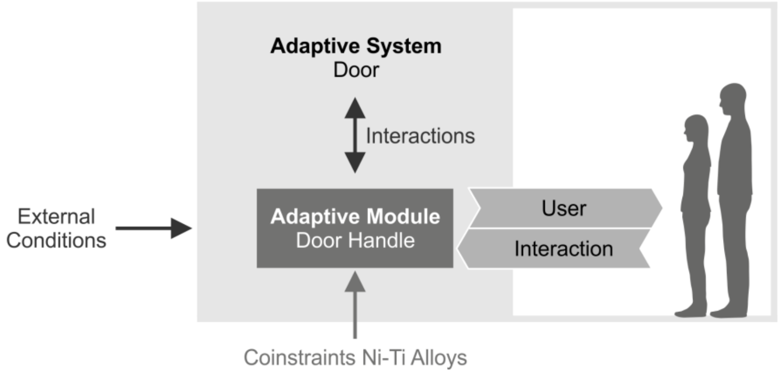

Figure 6. Initial scheme to design Ni-Ti human-machine interfaces.

The external conditions of the environment are mainly changes in the surrounding temperature. External conditions of the system comprise installation space, (above all one direction matters, as wires are almost one-dimensional) and the tolerable temperature for other system components.
There are also constraints defined by the material Ni-Ti. For example, the permissible and the required transmittable voltage, strain and stress are important. Additionally, the activation and deactivation (time, type and response time) have a significant influence on the system behavior.
Regarding the design of the adaptive system, the system itself and the adaptive module have to be considered. Thus, the mode and state of motion have to be specified. On the one hand, there is the movement of the alloy, on the other hand, there is the requested movement of the system. Therefore, structure and shape must be designed. Within human-machine interfaces, it is essential to avoid additional strain and stress on the alloy through the user. To design fitting structures the operation mode has to be defined as it affects the applied force (handle: pull, button: push). It is important that structure and shape support the deformation of the body structure, for example due to low bending stiffness. The required states have to be designed optimally regarding comfortable, reliable and accurate operation. As there is a direct contact between adaptive system and user, ergonomic and aesthetic shapes gain relevance.
Unlike other SMA actuators, human-machine interfaces are connected to the user. Therefore, specific requirements have to be considered: maximum operating temperature of the device, anthropomorphic shape, operating force and comfort of use.
Links and interactions arise between the four main elements. Adaptive modules and adaptive systems interact mainly through their mechanical connection. The sub-material of the adaptive system has to be temperature and stress resistant (prevent overheating and cuttings). There has to be an even and precise attachment of the crimp connectors to avoid uneven movements. If resetting is required, the defined resetting system has to be connected to both adaptive module and adaptive system (material stiffness, structural shape). User and adaptive module interfere for example through the temperature and the shape of the module. The tolerable temperature regarding the user does not necessarily match the operating temperature of the adaptive module.

6 Conclusion and Outlook

Usage of smart materials in product design will continue to increase, as the advantages are obvious: additional functionality without adding mass and volume combined with the possibility to design individual and ergonomic products.
In general, it can be stated that there is a lack of standardization and practically applicable methods, above all, regarding human machine interfaces. There exist methodical approaches (for example VDI 2248) but those are often too general and include few suggestions on how to actually design a Ni-Ti actuator.
This paper offers a first step towards efficient and effective design with smart materials. The application matrix supports the possibility to derivate new products from current ones. Thus, existing knowledge can be used, and further research can be done in optimizing the products.
Further investigation will be done in designing and building up additional prototypes to gain experience in human machine interfaces using Ni-Ti alloys. Based on this, design parameters including concrete implementations will be derived. This will lead to a setup of an operational prototype and a method for designing human machine interfaces using Ni-Ti alloys.

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