INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11
15 - 18 AUGUST 2011, TECHNICAL UNIVERSITY OF DENMARK

SIGNIFICANCE OF REQUIREMENTS FOR THE IMPLEMENTATION OF NEW TECHNOLOGIES USING SHAPE MEMORY TECHNOLOGY

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ABSTRACT

In this paper the assumption of a conflict between existing requirements and the application of new technologies will be illustrated by using examples based on shape memory technology. For this purpose, two product concepts are analyzed. Starting with the planning phase and the definition of system requirements, the described design processes also include conceptual, embodiment and detail design phases. Special attention is paid to the specification of requirements and their effect on the respective product concept. The aim of this paper is to identify influences on the product concept caused by the conflict between existing requirements and the application of new technologies. Certain requirements, e.g. historically based requirements, prevent the application of those new technologies in many cases. Therefore, the application of new technologies in combination with established requirements is investigated and then re-evaluated after the adaption of critical requirements.

Keywords: new technologies, shape memory alloy, actuator, requirements

1 INTRODUCTION

Shape memory alloys (SMA) exhibit the remarkable property to recover a previously imprinted shape after a deformation. That effect can occur either at constant temperatures (mechanical memory, pseudoelasticity), or changing temperatures (thermal memory). Both effects rely on the martensitic phase transformation [1]. This paper focuses on the thermal or actuator effect in combination with restoring force devices, the extrinsic two way effect [2]. There is a wide area of applications for shape memory devices. Due to their unique advantages, like mass decimation, high pulling forces and noiseless actuation, SMA actuators can be used in automotive, aeronautical and maritime applications or in consumer products. Generally, SMAs can substitute a large quantity of conventional drives.

One problem is that shape memory actuators are often misjudged by system developers who are not familiar with this technology. Other problems are the critical requirements for this technology. These requirements are for example the ambient temperatures, the width of hysteresis, the cycle time and the stability of the effect.

The first example of a product concept in this paper, a readjusting system for a ventilation flap, is used to clarify that further development of shape memory technology can lead to a fulfillment of requirements that could not be fulfilled in the past. However, the possible fulfillment of the requirements is still mostly unknown.

The second example in this paper, an unlocking system for a glove box, is a concept which was strictly elaborated according to the requirements of the company. In this case, a set of problems occurs because the concept is highly complex and cannot compete with established solutions due to its high requirements. In most cases the adaption only means changing one or two requirements, and their quantitative characteristics. The modifications lead to a considerable simplification of the respective concept without reducing the quality of the desired functionality.

2 CLASSIFICATION OF REQUIREMENTS

The systematic classification regarding the fulfillment of the product requirements for SMA based applications is presented in *Figure 1*. The requirements result from the product specification and have to be classified for each system. The requirements do not belong to the technology itself, but the requirements influence the parameter value of the technology or the implementation of the technology. Generally, three main categories can be distinguished: fulfilled, partly fulfilled and non-fulfilled requirements. Fulfilled requirements are marked with a green light, partly fulfilled requirements are marked with a yellow light and non fulfilled requirements are marked with a red light. The mark of the requirements with different colors is important for the classification of product requirements in the following examples.

2.1 Fulfilled requirements

Compliable requirements can be divided into conventional and new requirements. Conventional requirements are not to be considered as a problem for the implementation of new technologies but at the same time there are no decisive product advantages and innovations. In contrast to that the fulfillment of new requirements are to be considered as the main advantage of new technologies. These new technologies make product innovation possible at all. Shape memory technology involves the following new requirements: constructional space, weight, sound emission and the simplicity of the system. Furthermore, new requirements can be demanded with regards to functional integration. Especially due to the application of SMAs, highly integrated components can be generated (partly combining all functions in one single component) [3, 4].

Besides functional integration, standardization as a new requirement is of great importance. In this case, functional materials like SMAs provide unique possibilities. In case of standardization, the common approach of variant construction is turned upside down and the variety of variants in terms of SMA-actuating elements is reduced dramatically. This new view regarding variant generation of components is comparable to the production of circuits in information technology (IT) [5]. The final function definition is applied during the design phase on the principle of base structures as well.

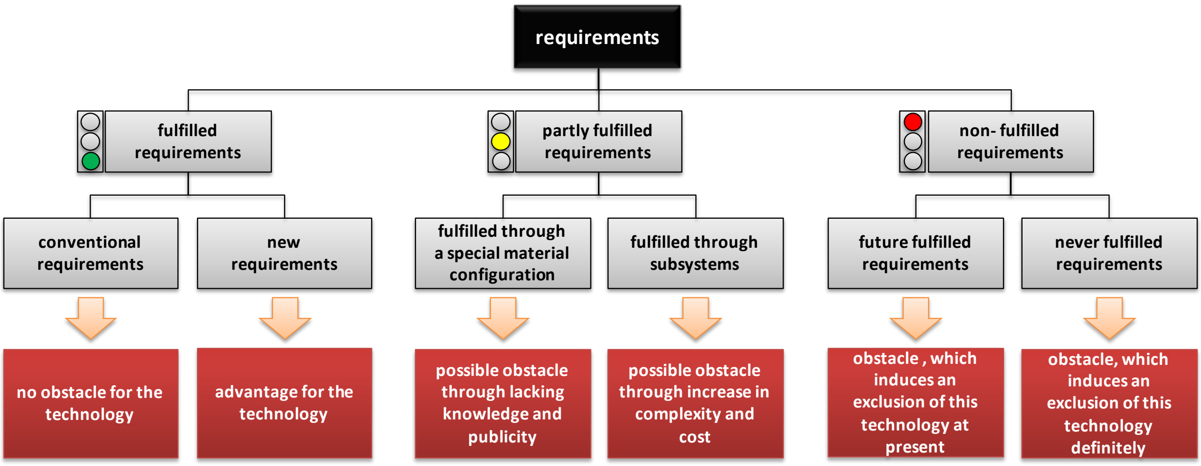

Figure 1. Classification of requirements for SMA applications

2.2 Partly fulfilled requirements

Such requirements are a first obstacle for the application of new technologies. Partly compliable requirements cannot be fulfilled by standard materials. Yet to meet these requirements, there are two possibilities.

Firstly, specific configurations of the material can provide the desired quality of the function. In case of shape memory technology, special material properties like the R-phase transformation need to be mentioned. The temperature hysteresis can be reduced from approx. 20K to approx. 3K by conversion [6]. In this way, the temperature controls can be accomplished more accurately. The readjusting system, explained in the subsequent chapters depends on this low hysteresis. Applications based on these special material configurations are hard to find due to a general lack of knowledge.

Secondly, non-compliable requirements of a material can be fulfilled by a connection of additional mechanical or electrical systems. In terms of SMAs, transformers are commonly used such as sets of levers, and diverter pulleys, in order to meet the requirements according to displacement and pulling load in an adequate installation space. Mechanical interlocks and energy storage are also used to keep positions currentless or to return to default safe positions. Such requirements are dealt with in the following chapters using a second example, the unlocking system. The problematic issue about these systems is that the connection of peripheral sub-systems increases the complexity of the entire system and therefore advantages compared to conventional positioning elements do not exist any longer.

Furthermore, it can be realized that certain requirements of technical systems do not meet today's structural conditions. One reason is that requirements haven't been adapted to further technical developments. Another reason is that requirements cannot be cascaded to sub-systems but they can only be set up globally for the entire system. The development of the "glove box opener" [7] will seize and explain this aspect in detail again.

2.3 Non-fulfilled requirements

Such requirements are obviously a massive obstacle for the application of new technologies. It must be differentiated between generally non-compliable requirements and those requirements non-compliable to today's state-of-the-art technology. In order to fulfill the latter requirement, a further technical development must take place. Partially, laboratory samples are already available but an industrial realization has not been accomplished yet. In case of SMAs, high temperature alloys [8] have to be mentioned. These alloys have transformation temperatures above 200°C and therefore are mostly suitable for applications in vehicles. Due to the bad formability of these alloys semi-finished products like wires are not available. However, new alloying elements will solve this problem in the future. Nevertheless, such further technological developments require an enormous research until a secure and reliable application can be guaranteed.

3. FIRST EXAMPLE: READJUSTING SYSTEM FOR A VENTILATION FLAP

3.1 Basic principles

This system is an example how special material properties help to fulfill non-compliable requirements like the temperature hysteresis. The special material property can be identified as R-phase transformation in this case. Depending on the thermo-mechanical pre-treatment and the chemical composition of the alloy an intermediate phase (R-phase) occurs during the transformation of NiTi-SMA from the high temperature phase austenite to the low temperature phase martensite. The R-phase has a rhombohedral crystalline structure resulting from the distortion of the austenitic body-centered cubic crystalline structure. During the phase transformation of the austenite into the R-phase only few shear strains are observable and therefore the temperature hysteresis is only 1K to 3K [9], [10]. Compared to the phase transformation of austenite into martensite the temperature hysteresis is between 20K and 40K. The minor shape memory effect (only approx. 0.8% [1]) is a huge disadvantage using the technical application of R-phase transformation. In comparison the shape memory effect of the phase transformation of austenite into martensite is approx. 7%.

Working against the disadvantages of the R-phase transformation and its small effect of displacement, the shape memory effect must be converted with a corresponding transformer. Using the design of the R-phase actuator as a helical spring the conversion is integrated into the actuator element. The usable effect value can be regulated by the number of turns. The usable pulling load results from the thickness of the wire and the turn ratio.

3.2 Development of the actuator system

Consecutively the design process of "readjusting a ventilation flap" regarding an actuator system is presented. This flap controls the air mixing ratio between working and fresh air in an RV. The conventional system is a mere mechanical solution. The ventilation flap is shifted between the positions "maximum fresh air supply" and "maximum working air supply" according to requirements via a bowden cable inside the vehicle interior. The position of the mixed air ratio should now take place automatically for comfort reasons.The development of the actuator systems took place on the basis of product development phases planning, conceptual design, designing and elaboration. *Figure 2* shows the principle of the ventilation flap system at the moment.

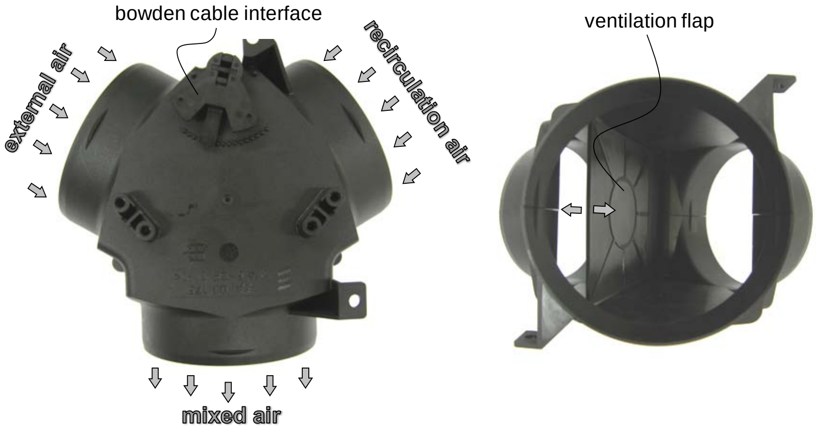

Figure 2. Ventilation flap system

3.3 Requirement Model of the readjusting actuator

At first, requirements for the actuator system are defined and compiled during the planning phase. With a conventional SMA, the requirement of a lower temperature hysteresis cannot be realized. To realize this requirement easily with conventional SMA and to get a green light, the temperature hysteresis should be located at approx. 20°C. But in this case, the hysteresis requirement can be identified as a partially compliable requirement, illustrated with a yellow light. For this reason the requirement should be proved and solutions have to be searched. One solution for the hysteresis problem could be the usage of an alloy with a R-phase effect.

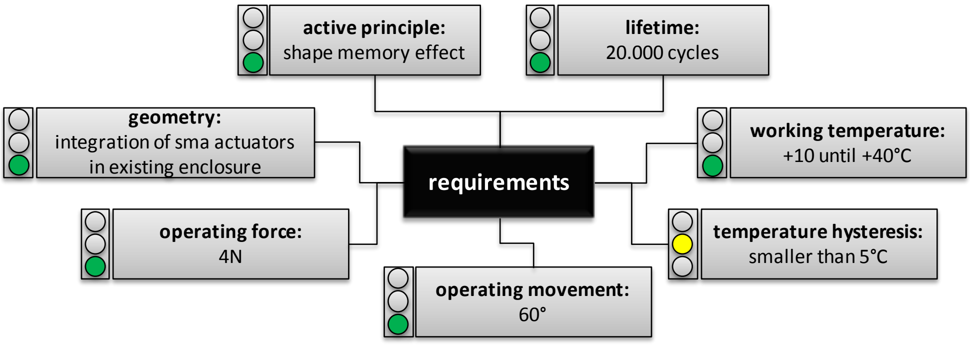

Figure 3. Requirements for the ventilation flap system

3.4 Functional model of the readjusting actuator

In order to solve the problem the conventional system is analyzed during the concept phase and particular sub-functions are identified. At the same time specific sub-functions of SMAs are compiled (e.g. “transferring heat into energy” and “putting back actuator elements”). After that all essential functions needed for the configuration of the actuator systems are put together in one function structure (*figure 4*). Unnecessary functions of the current systems (based on electric motors) are substituted like the conduction of the mechanical energy via a bowden cable.

Usually the actuator performs activation depending on the ambient temperature and so it changes continuously between the position “fresh air supply” and “working air”. If it is warm the flap should be in the “fresh air position”, if it is cold the flap should be in “working air position”. Therefore, thermal energy remains inside the system. This energy is converted into mechanical energy via the SM-actuator with increasing temperature. Then the mechanical energy is transferred from the SM-actuator to the ventilation flap. As the R-phase actuator performs a linear movement an additional forming function must be provided, which converts the translation into rotation. If the ambient temperature increases the flap must be moved back to the position “fresh air”. This should take place via a reset element according to the two-way effect [2]. If the operator wants to readjust the flap himself the SM-element can be activated by electric energy.

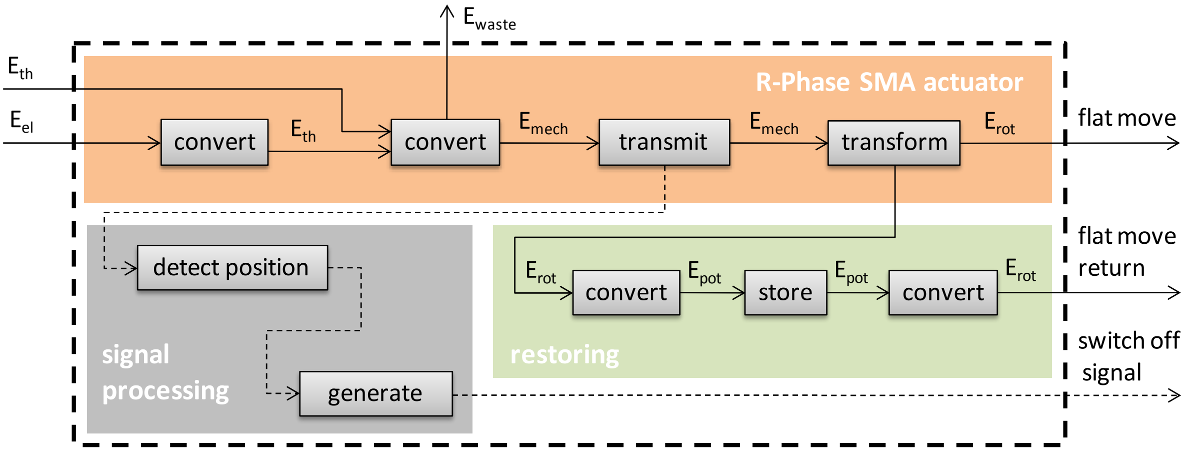

Figure 4. Functional structure of the ventilation flap system

3.5 Principle model of the unlocking actuator

In the next step different concepts of the actuator system are generated from the function structure. For this purpose active principles are taken from individual sub-functions to connect them to useful concepts. *Figure 5* depicts the favored concepts of the readjusting mechanism.

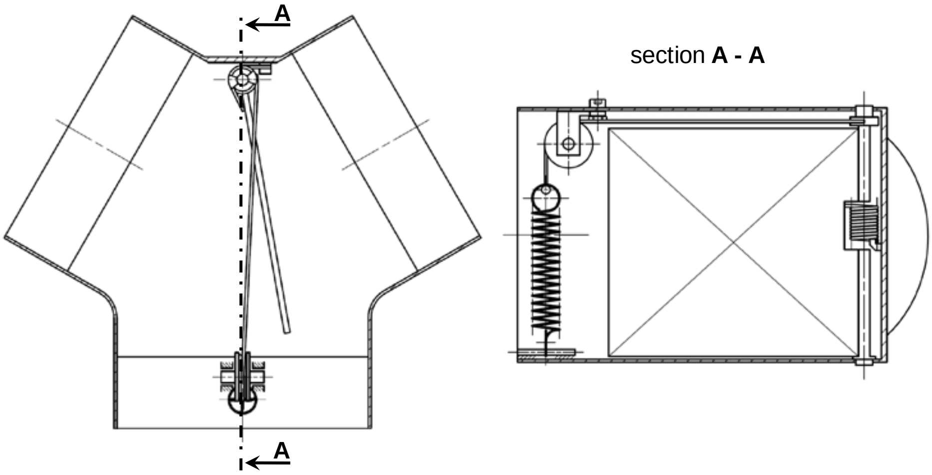

Figure 5. First concept of the ventilation flap system

The SMA-actuator is placed inside the mixed air duct where fresh air and working air are mixed up. A wire is used to transmit the mechanical energy from the actuator to the rotation axis via a diverter pulley. The translatory motion converted into a rotary motion via a transformer. The resetting of the shape memory spring at low temperatures into an extended condition is caused by a yoke spring attached to the rotation axis. If the spring is heated it contracts and generates the setting motion which leads to the adjustment of the flap to the position “fresh air”.

3.6 Dimensioning of the actuator components

After the creation of the concept the basic design and the characteristics of the actuator element are determined during the design phase. The phase transformation of the spring actuator provides the mechanical energy for the adjustment of the ventilation flap. The actuator must be designed and dimensioned according to the amount of energy released. The design takes place according to the approach of Otsuka [1]. The characterization of the SMA-actuator takes place in an activation test stand where a constant load is attached to the actuator spring. The load elongates the spring to a certain value. After that the ambient temperature is increased. The beginning phase transformation contracts the spring and lifts the load. When the ambient temperature is decreased, the spring elongates again.

3.7 Concept of the unlocking actuator

After the design and the dimensioning of the SM-actuator the reset spring and the components of the system, a CAD model was constructed and a first prototype was produced. *Figure 6* shows the corresponding results of the design phase.

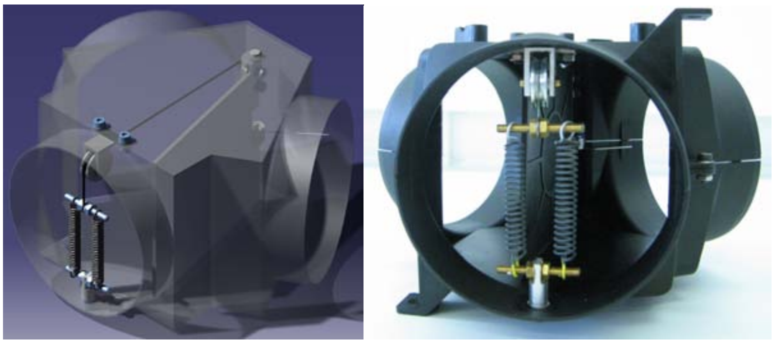

Figure 6. CAD model and prototype of the SMA based ventilation flap system

3.8 Assessment of critical standards

This example identified the temperature hysteresis as partly compliable and therefore critical requirement. The problem coming along with this critical requirement was solved by the application of R-phase transformation. The system presented, shows the applicability of shape memory technology in fields of application where a low temperature hysteresis is required. So the application potential of this technology can be extended, assuming that such material effects and configurations are known and can be handled constructively. Unfortunately, this is not the case. The lack of communication between industry and universities leads to a deficit in distributing new technologies. The transferred technology must be recognized officially and become more important.

4. SECOND EXAMPLE: UNLOCKING SYSTEM FOR A GLOVE BOX

4.1 Introduction

This system is an example how peripheral systems can fulfill non-compliable requirements. Especially in a vehicle, where requirements with high operating temperatures predominate, this strategy is of great importance. The vehicle thereby offers many potential applications for the employment of shape memory alloys. The applications in the interior of a vehicle such as seat control functions, unlocking and locking mechanisms for doors, glove boxes and petrol caps have so far been implemented with comparatively heavy, sound-emitting electric motors. Concerning these points, SMA can offer decisive advantages.

4.2 Requirement model of the unlocking actuator

For the development of the unlocking actuator the requirements of the original system together with the solution of the electric motor were taken as a basis and supplemented by several specific requirements. The SMA unlocking actuator for example was to be integrated in the latch of the glove box.

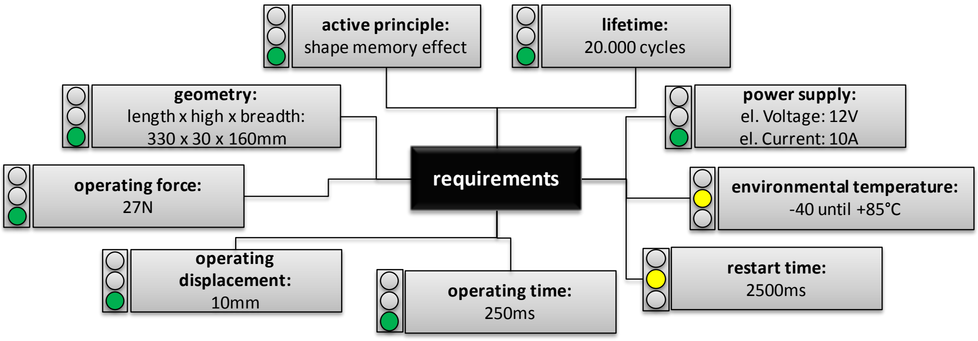

Figure 7. Requirements of the SMA actuator for unlocking tasks

The requirement of a reactivation time of 2500ms after the first opening of the glove box and the requirement for operability of the mechanism in ambient temperatures between -40°C and +85°C have been identified as critical for the SMA unlocking actuator and for this reason flaged with the yellow light. Commercially available SMA wires possess a martensite finish temperature of approximately 65°C [11]. Therefore, ways to increase this temperature by technical means must be found. In consideration of the expected wire diameter, a reactivation of the actuator in the required frequency f = 0.4 1/s cannot be realized. Accordingly, redundant actuators have to be planned, which trigger the unlocking function one after the other.

4.3 Functional model of the unlocking actuator

Based on the determined requirements a functional structure was designed which comprises the function blocks of actuator (stacks), transmission, locking mechanism and sensor and signal processing (see *Figure 8*). Electrical energy serves as the input parameter, mechanical energy as the output parameter. This complexity of the functional structure is due to the aforementioned crucial requirements, which necessitate the redundancy of the SMA actuators and a decoupling of these systems.

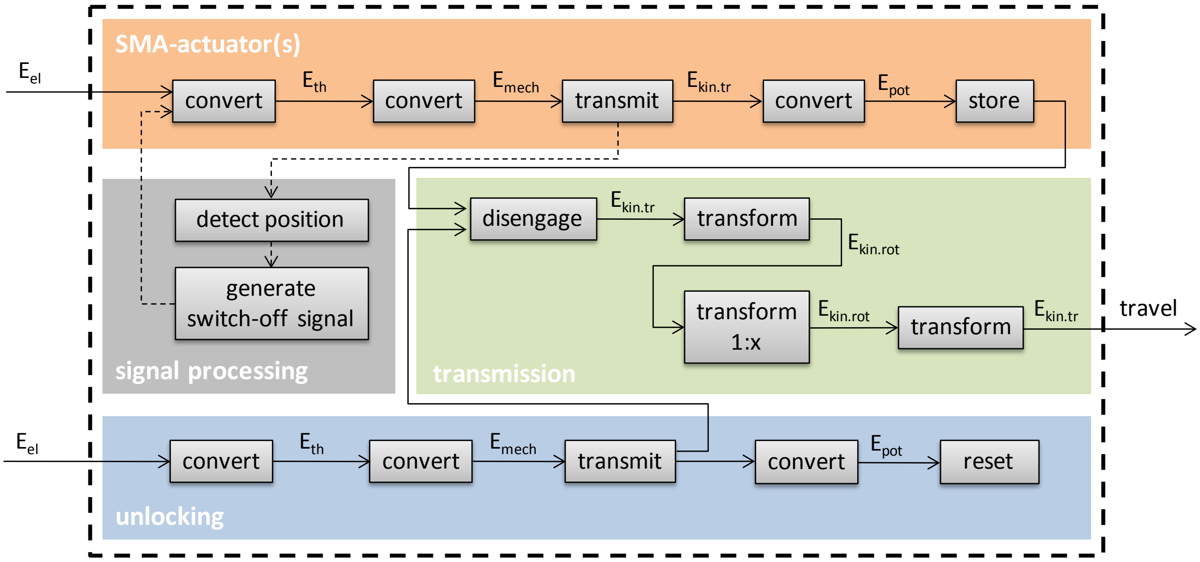

Figure 8. Functional structure of the SMA actuator for unlocking tasks

4.4 Principle model of the unlocking actuator

The principle model of the unlocking actuator derives from the functional model. Active principles are determined for the respective functions by using creativity techniques and are evaluated according to technical and economical criteria.

The most highly evaluated active principles are transferred to concepts. *Figure 9* shows a concept that consists of a mechanical energy store, which is charged by means of an SMA actuator.

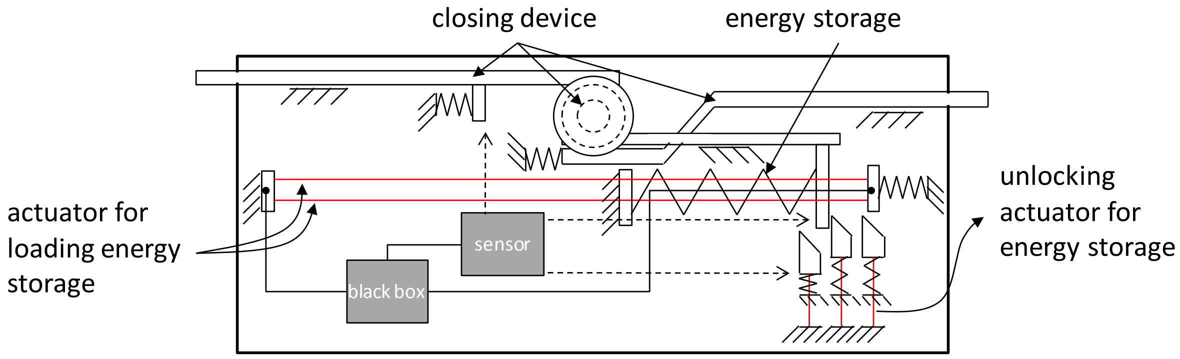

Figure 9. First concept of a SMA actuator for unlocking tasks

Subsequently, this energy store is partially discharged again using several unlocking actuators. On the one hand, the use of the energy store increases the dynamics of the system, on the other hand the force necessary for opening the glove compartment is reliably provided. The partial discharge has the advantage that the unlocking actuator can safely complete the required function even with high ambient temperatures, because it has to operate only once per charging process of the energy store. Through this action, the influence of the martensite finish temperature of the SMA actuators on the opening mechanism is minimized. Since the glove box actuator in the depicted diagram possesses three unlocking actuators, the unlocking function is guaranteed three times as well, up to an ambient temperature of approximately 120°C. Subsequently, the energy store needs to be recharged again.

4.5 Dimensioning of the actuator components

The extrinsic two-way effect is applied for the unlocking process according to the principle of actuator with restoring force (cf. *Figure 9*). In the following, the dimensioning of the actuators is exemplarily considered. The dimensioning of the actuators occurs under consideration of the criteria transformation temperature, actuating force, displacement, actuating times, cooling times, durability and connection method (cf. [12]).

A commercially available binary NiTi with an austenite start temperature of 90°C and a martensite finish temperature of 70°C is used as an actuator alloy. Due to the forces working in the system, an SMA wire with a diameter of 0.3mm and a length of 70mm is opt-in for unlocking actuators. A durability of over 10,000 cycles is expected. In order to reach the reaction time of the system of 0.25ms according to the requirements, activation attempts of the actuator wire using Joule’s laws are carried out. It is obvious that the cooling time is the crucial figure. If activation times can be compensated by higher currents at increasing wire diameters, diameters above 0.3mm irrevocably show a cooling time beyond the required 2.5s.

In an activation attempt the displacement and dynamic of the actuator is assayed at different ambient temperatures (cf. *Figure 10*). Due to the decreasing thermal gradient between the SMA wire and its surroundings at a rising ambient temperature, the amount of dissipated warmth also decreases. For this reason, the cooling rate slows down considerably. At 20°C the cooling rate amounts to about 2.5s, at 70°C it amounts to as much as 20s. So the shifting time does not meet the high requirements at these temperatures. A realization of the system with a basic actuator element is impossible under these circumstances. The requirement of a shifting time of 2.5s is a partly compliable requirement. In order to meet these requirements the application of redundant actuator elements is possible. If the ambient temperature is increased further to 85°C one can see that at 85°C the recovery of the SMA wire cannot be observed anymore as its martensite finish temperature is below 85°C. So another partly compliable requirement occurs. An alloy which meets these requirements is non-commercial and not available yet.

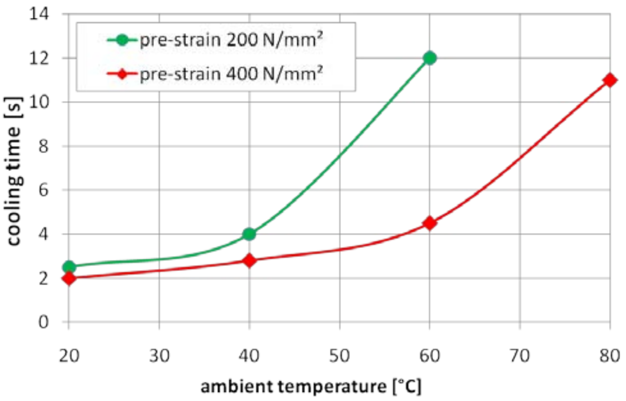

Figure 10. Cooling behavior of a SMA actuator wire

In order to reach the required 85°C it is necessary to increase the pre-stress of the SMA wire. *Figure 10* shows the displacement of the same wire under a pre-stress of 400N/mm^2, too. Here it is observable that the resetting also takes place at ambient temperatures of 85°C. However it is problematic that the fatigue behavior increases significantly at high pre-stresses. That means that due to the fulfillment of ambient temperature requirements, the requirements of the shifting cycles are non-compliable. As a result an increase of the pre-stress is not useful, but a mechanical sub-system is needed instead to fulfill the requirements. During the development process a spring accumulator turned out to be a good sub-system. It provides energy for shifting processes in four stages. The spring accumulator in form of a coil spring is pre-stressed via a shape memory element. The pre-stressed actuator itself is no longer subject to the high requirements concerning shifting time and ambient temperature.

4.6 Concept of the unlocking actuator

After dimensioning all actuator components and the implementation of different optimizations, the following concept of a glove box unlocking actuator has been developed (*Figure 11*).

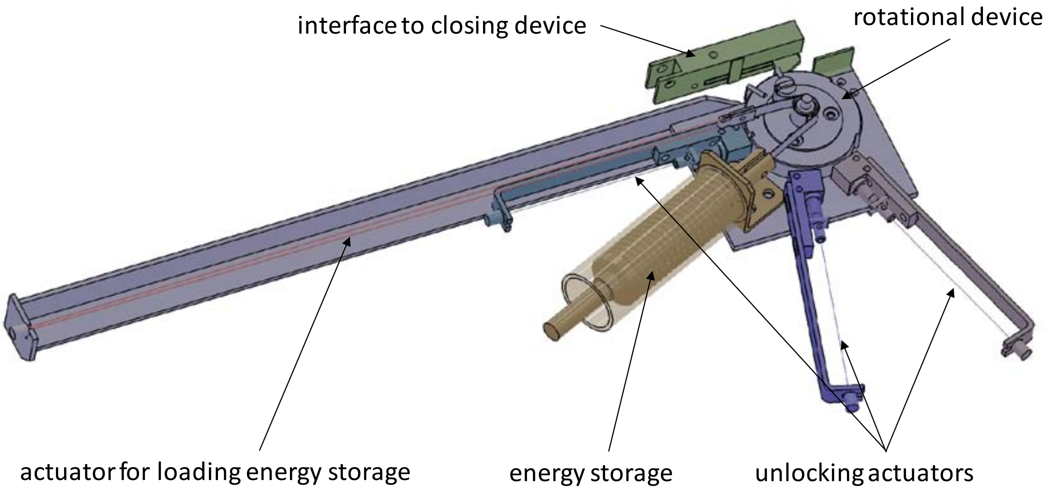

Figure 11. SMA actuator for unlocking tasks

Just as the concept, this actuator consists of an energy store and three unlocking actuators, which serve the disengaging of the energy store. The actuator, including its electronics can be completely integrated into the latch of the glove box.

4.7 Assessment and adaption of critical standards

The concept in *Figure 12* shows that if all requirements are fulfilled a system emerges which is not competitive compared to conventional actuation mechanisms (electric motor and electro magnets).
Because of the sub-systems the unlocking actuator becomes too complex losing the characteristics of the technology, namely to provide simple solutions. At this point it is time to think about whether certain requirements are feasible. SMA's have low reconversion temperatures but considering the actual positioning process the switching temperatures are approx. 110 °C. That means at 85 °C inside the vehicle interior the glove box would not open itself. If one opened it, no further positioning process would happen at these temperatures. But who sits in his vehicle at 85°C and opens his glove box a couple of times? If one lowered the ambient temperature to 70°C a simple system could be used. Such a system is shown in *Figure 12.* The requirement regarding the shifting time is fulfilled by three redundant actuator elements. If the automobile industry cannot adapt to such requirements, the application of SMA's is not advisable in this case.

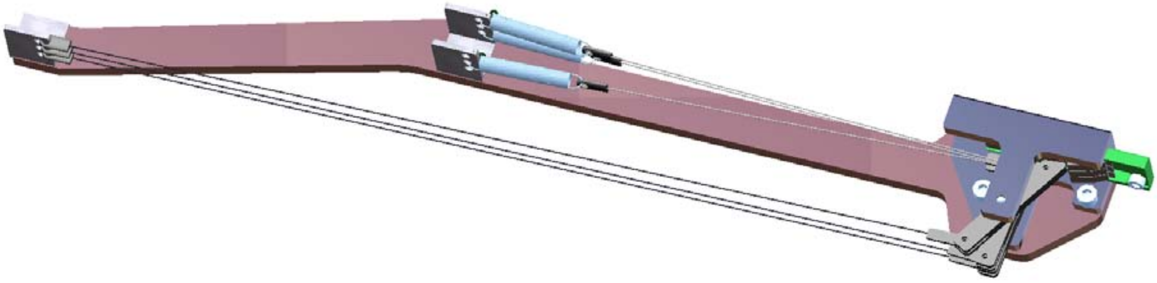

Figure 12. Reengineered SMA actuator for unlocking tasks

5. CONCLUDING REMARKS

The increasing demand for comfort and the associated new functions make the utilization of new technologies, e.g. SMA technology essential. Identified obstacles for the application of this technology are only partly fulfillable or not fulfillable system requirements. The presented examples of product developments have shown the consequences of critical requirements for the design process of the products. The example of the ventilation flap system (see Fig. 7) has shown that apparently not fulfillable requirements can be achieved by a further development of technology. The lack of knowledge of companies about such developments is however a big problem which needs to be solved, regarding the implementation of such technologies. The second example, the unlocking system, has illustrated a different kind of conflict. This conflict cannot be solved by the material itself, but requires additional mechanical sub-systems. A problem here is the increasing complexity of the system. In such cases, the application of SMA technology has to be thoroughly investigated before the start of the design process. In order to clear the way for new technologies, the significance and feasibility of requirements must be reviewed and is of paramount importance, as shown in the second example. The final conclusion is that only by adjusting critical requirements, creating profound marketing strategies and carrying out further research in this area, new technologies can be successfully implemented.

AKNOWLEDGMENTS

The authors acknowledge funding by Deutsche Forschungsgemeinschaft (DFG) within the framework of project T4 of SFB 459 (collaborative research center: Shape Memory Technology).

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