Development and Implementation of a Guideline for the Combination of Additively Manufactured Joint Assemblies with Wire Actuators made of Shape Memory Alloys

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Abstract

Smart Materials actuators in the form of wires made of shape memory alloys in combination with additively manufactured carrier components are used in a wide variety of prototype developments of innovative joint assemblies. This combination is relevant because of the same manufacturing costs of the additively manufactured components, which are independent of the quantity of parts, the free geometric design possibilities as well as the huge energy density of the aforementioned actuator technology. In particular, the focus is on the possibility of appropriately fitting large wire lengths on a compact part volume while taking into account acceptable force losses. Since there is no design guideline for such joint developments, each is individual, which results in unnecessarily long development times and a higher risk of errors. Based on selected in-house and third-party examples, integration possibilities of shape memory alloy wire actuators in additively manufactured carrier components are analysed and transferred into a universally applicable design guideline. These recommendations are brought into the framework of existing design guidelines of the VDI (Verein Deutscher Ingenieure – Association of German Engineers), namely VDI 2206 and VDI 2221 with extensions for additive manufacturing, for a better usability and integrability into existing processes. Finally, this results in a simplified access to the topic of the combination of additive manufacturing and shape memory alloys and a more efficient realisation of such joint developments.

Keywords: Design Guideline; Additive Manufacturing; Smart Material; Shape Memory Alloy;

1. Introduction and Motivation

1.1. Introduction

The current economic and environmental situation demands the development of resource-efficient, energy-saving and lightweight actuators. Smart materials (SM) in the form of shape memory alloy (SMA) wire actuators are suitable for these actuator developments. These actuators are characterised by the highest known energy density [1], from which large forces can be realised in joint assemblies in a small installation space with minimal material usage. SMA actuators generate their movement through a reversible phase transformation from martensite to austenite, which is done via Joule heating [2, 3]. The movement form depends on the so-called training of the actuator. With a wire actuator, it is usually a contraction of the wire. There has been a significant upward trend in the number of patents registered and papers published in recent decades [4]. Examples of application and research projects are pneumatic valves [5], a suction cup gripper [6] as well as a bionic bat [7], hand [8] and owl neck spine [9]. A broad study for further applications can be found here [4]. The disadvantage of these actuators is the comparatively small stroke of 3-5 % [10]. However, it is possible to fit large wire lengths into small

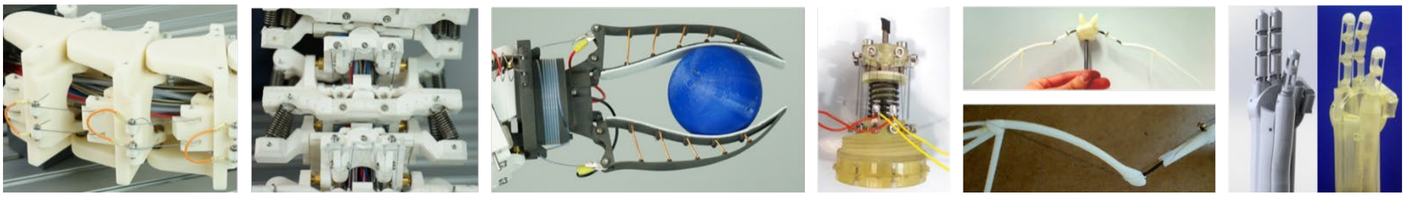


Figure 1. Examples of SMA+AM prototypes. From left to right: 1-3 owl neck joints and gripper, suction cup gripper [6], bionic bat (MAV) [7], bionic hand [8]

installation volumes by appropriately arranging the wire actuators. The resulting friction losses between the SMA wire and the carrier component must be taken into account and evaluated. For the manufacturing of such SMA wire actuator systems, additive manufacturing (AM) is a suitable option due to the now very easy accessibility, the constant manufacturing costs, which are unaffected by the quantity of parts, the lightweight design potential, the wide variety of materials as well as the great geometric design freedom. In addition, at least desktop 3D printers can now be found in most research facilities in product development and related research areas. For this, a variety of AM processes, for example Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS) or Selective Laser Melting (SLM), can be used as long as the mechanical and thermal properties of the printing materials are sufficient. The strengths described are particularly crucial in the production of prototypes and small series.

Because of the described spread of these two technologies and especially due to the complementary properties for good geometric integrability of the wires, overlaps arise, resulting in AM carrier components with integrated SMA wire actuators [8, 9, 11, 12]. From here on, these joint assemblies will be referred to as SMA+AM joint assemblies.

These research and development projects are always individual solutions, resulting in long development times and increased risk of errors. There is no specialised guideline to facilitate the entry into prototype development for AM carrier components with integrated SMA wires and to accelerate and secure the development process. This guideline, which is currently being developed in the form of two design catalogues, is presented in this article and integrated into existing frameworks for product development.

In these joint assemblies, the actuator wire is installed after the additive manufacturing of the carrier components. In this way, the assemblies described here differ from so-called 4D printing processes, in which complete SM actuator assemblies are produced with established AM processes [13]. In 4D printing, for example, shape memory composite (SMC) actuators are produced by a combination of SMA and shape memory polymers (SMP) using the FDM printing process [14] or whole SMA actuators by the SLM printing process [15].

1.2. Motivation

The problems in the development process of SMA+AM joint assemblies also occurred in a research project of the author. This led to the idea of developing the guideline described in this article. For this reason, the following describes how the development process took place in the author's project, what the results were and how the development process could have been improved. To further highlight the need for a guideline, the results of three other research projects with SMA+AM joint assemblies, from a research institution that is very experienced in this field, are also described.

A bionic joint robot arm was developed by the author as part of the aforementioned research project [9]. This robot arm is based on the model of the flexible cervical spine of American barn owls. The development of the robotic arm was time-consuming and many iterations had to be carried out to reach a functioning prototype. Time losses resulted initially from not knowing the performance and resource saving potentials of SMA wire actuators for such a project. Extensive comparisons had to be made with various actuator technologies, such as electroactive polymers, piezo actuators, thermobimetals, pneumatics and hydraulics. Subsequently, the integration of long SMA wire lengths, as a muscle substitute, into the delicate vertebrae structures of the technical owl's neck had to be dealt with. While examples from other research projects could be used, as described later in this chapter, simplified experiments on wire integration had to be carried out. After that, three basically different joint assemblies were developed in many iteration steps (see in the left half of Figure 1). On the one hand, the SMA wires were executed by bowden cables with subsequent local deflection points in the form of simple pulleys or PTFE tube sections in a pulley arrangement. On the other hand, the SMA wires were helically wrapped around the basic gripper body in Teflon tubes. The focus was always on fitting large wire lengths with acceptable friction losses. In the pulley arrangement, a load reduction of the SMA wires in the factor of the pulley ratio is also achieved. In this arrangement, larger loads can be moved without risking damage to the wire. With a corresponding guideline for the integration of SMA wire actuators, the author could have carried out the development process faster and more cost-effectively.

On the right side of Figure 1 third-party research projects using the combination of SMA wires and AM carrier components are shown. From left to right, this is a suction cup gripper with SMA wire actuators arranged in a circle like a pulley. The inner hook spring pulls the suction cup upwards and thus holds the respective workpiece in the energy-free state of the SMA wire actuators. To release the workpiece, the SMA wire actuators pull the outer ring upwards and the suction cup is pressed flat [11]. In the joints of the bionic bat, a micro air vehicle (MAV), the SMA wire actuators are placed outside the pivot point, from which a contraction moves the bat's wing in the appropriate direction [12]. In the bionic hand, the SMA wires are also placed off-centre from the centre of rotation and produce the corresponding bending and extending movement of the individual fingers in an agonist-antagonist arrangement [8]. These examples could be successfully realised due to the intense research activities in the field of smart materials, especially SMA, of the research institution involved.

A lot of experience is therefore necessary for the development of such joint assemblies. For researchers and engineers without, or with limited, experience in this field, a corresponding guideline could at least facilitate the start and accelerate the learning process. This is intended to be supported by integrating the guideline into a framework that is familiar to the user, such as the VDI.

2. A short Review of existing Frameworks

The following VDI guidelines already exist to support the general product development process of various technical systems, the design for AM and also the development of SMA actuator systems. The SMA+AM specialised guideline described in this article is to be integrated into this framework. Attention has been paid to ensuring that all documents are available in English.

2.1. VDI 2206 Development of mechatronic and cyber-physical systems [16]

As additively manufactured and SMA driven joint assemblies are mechatronic this existing framework is the right place to contribute a specialised guideline.

In this framework, the so-called V-model (see Figure 4) is used to break down complex mechatronic tasks into individual subsystems of the respective disciplines (mechanics, electrical engineering, software engineering) as you can see in the left branch of the V. These individual subsystems are processed in parallel, continuously verified and validated (middle part of the V) and then integrated back into an overall system (right branch of the V). The system architecture in particular is crucial for the interaction of the two relevant disciplines of mechanics and electronics for the development of SMA+AM joint assemblies. It describes the interaction and integration of these two disciplines, which can lead to more compact modelling and physical systems. This can result in the development of a separate V-model for the design of an SMA+AM joint assembly, which is then integrated into the overall V-model.

2.2. VDI 2221 Design of technical products and systems [17]

This guideline forms the basis of most engineering product development processes with the help of a product development model. The process is decomposed into defined activities and continuously compared with the required results. The previously described V-model can be used in sub-steps within the framework of this holistic process. At the same time, the requirements analysis described here is needed to be able to start with the V-Modell.

Exemplary activities with associated results are:

- Clarification of problem or task → Requirements
- Determination of functions and their structures → Function models
- Search for solution principles and their structures → Basic solution concepts
- Assessment and selection of solution concepts → Solution concept
- Subdivision into modules, interface definition → Systems architecture
- Shaping of modules → Partial designs
- Integration of product as a whole → Overall design
- Elaboration of execution and usage requirements → Product documentation

It is important here that the order of the individual steps is not fixed. On the contrary: iterative processes are desired and support creative solutions.

2.3. VDI 3405 Design rules for different additive manufacturing processes [18]

In this guideline, restrictive design rules for AM with various printing technologies (material extrusion, electron beam melting, ceramic material printing) are presented within various documents on the basis of geometric test shapes. Examples include maximum horizontal and minimum vertical hole diameters, maximum overhang angles and gap dimensions for moving or fixed parts. In addition, the individual printing processes, the printing materials used and the deviations to be expected in the form of tolerances and surfaces are described.

This knowledge is an important requirement for the design of the carrier components of SMA+AM joint assemblies.

2.4. VDI 2248 Product development using shape memory alloys [19]

These guidelines, with five available documents, currently provide an overview of various topics, such as material design, testing and measuring methods, as well as a development methodology of actuator systems in the field of shape memory technology. The basics shown in the guideline are intended to make it easier for researcher and engineers to get started in this field. A specially adapted V-model for the development of SMA actuator systems is available, which is shown on the right side of Figure 4.

3. Development of a Design Guideline for SMA+AM Joint Assemblies

To support researcher and engineers as best as possible in finding a quick solution for an SMA+AM joint assembly, the design catalogue is divided into two sub-catalogues. Firstly, there is a catalogue with core variants, in which the main features are listed qualitatively and in compact form (see Figure 2). Secondly, there is a much more detailed solutions catalogue, which deals with specific implementations of the core variants and quantitative performance specifications related to them (see Figure 3). It should be noted that both catalogues are under development and will be expanded in the future by analytical and experimental results.

3.1. Core Variants Catalogue

This catalogue is basically intended to provide ideas for the possible installation of the desired combinations of SMA wire

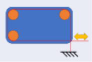
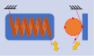
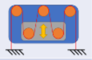
core variants	sketch	compact-ness	force multipli-cation	friction losses	reachable stroke	design complexity
straight		low	1	none	low	very low
deflection pulley		high	1	medium	high	medium to high
helix		high	1	high	very high	medium to high
pulley		medium	1 to x	medium to high	very low	high
⋮	⋮	⋮	⋮	⋮	⋮	⋮

Figure 2. Core variants catalogue for pre-selection of variants

actuators with AM carrier components, thus lowering the entry level. Through the qualitative data of the respective performance and design parameters, it is possible to select one, or more, core variant/s of the joint assembly at a very early stage of the project and thus carry out further evaluation processes. The further evaluation will be done with the solutions catalogue.

The following should be noted when working with the core catalogue. The criterion compactness refers to the geometrically appropriate or flexible installation of the SMA wire in the available installation space. For example, the straight mounted wire is therefore rated with a low compactness, as substitutable actuators are rarely very long and thin. The reachable stroke refers to this compactness. It is about how much stroke can be achieved with an actuator system that is as compact as possible.

Considering the use of SMA+AM joint assemblies as possible actuators in a project can also be done just by finding and examining the catalogue of core variants, as the presentation is intentionally kept simple and clear.

3.2. Solutions Catalogue

The solutions catalogue under development in Figure 3 will provide specific recommendations for the final design of the joint assemblies. The core variants will be further extended by example modifications in the form of pictures or sketches. These variants will be described in detail qualitatively and quantitatively on the basis of the relevant design parameters. The descriptions will include the possible potentials, but also the restrictions of the variants. During the detailed design, the user can make estimates about, for example, force and stroke losses due to friction, about the required installation space or the possibilities for additive manufacturing of the carrier components. The qualitative analyses will be supplemented by calculation approaches and test results on the final performance parameters of the joint assemblies, i.e. the expected force, the stroke and the activation or cooling time. The shortened table of the solution catalogue shown in Figure 3 is an example to illustrate the structure and will be completed with the described data in the future.

4. Implementation of the SMA+AM-Guideline in the VDI Framework

This section describes where an assistance in the form of a design catalogue can be usefully implemented in the frameworks described in chapter 2. It is important to note that for a holistic product development process, the framework according to VDI 2221 is normally used. If, for example, a less complex SMA+AM joint assembly is used within a project, it may be sufficient to directly use a suggestion from the solutions catalogue presented in chapter 3.2. Should the development process require a highly customised system of AM components and SMA wire actuators the V-model of VDI 2206 or VDI 2248 must be applied. The result of the V-model is then integrated back into VDI 2221.

4.1. Integration into V-model (VDI 2206 and VDI 2248)

Figure 4 shows the latest V-model of VDI 2206 [16]. The design ideas of the two catalogues described in chapter 3 can for the most part be used equally for this V-model and for the

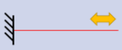
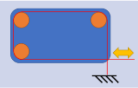
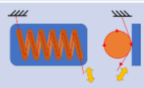
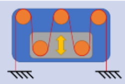
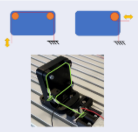
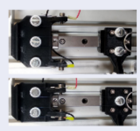
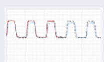
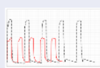
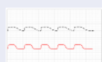
	straight	deflection pulley	helix	pulley	further concepts
sketch core variants					...
available solutions (sketch or picutre)	/				...
potentials of variants	- no friction - durability	- flexible installation space - larger stroke at compact installation space	- larger stroke at compact installation space	- reduced wire loard (in relation to movable wires) - Compact inst. space	...
restrictions of variants	- long/thin installation space	- force/stroke loss (friction) - complex design - increased material fatigue	- force loss/stroke (friction) - dynamic loss (thermal insulation wire)	- force/stroke loss (friction) - stroke loss (arrangement) - complex design - increased material fatigue	...
⋮	⋮	⋮	⋮	⋮	⋮
experimental analysis	- manufacturer information and experimental results	possible forces 	possible forces 	possible forces 	...

Figure 3. Structure of the solutions catalogue for the deflection variants of the SMA+AM joint assemblies

V-model of VDI 2248 [19]. The V-model of VDI 2248 is not presented separately here due to limited available space.

The subsystems (I, IV) of the V-model described hereafter, outlined in red and marked with red Roman numbers, are not covered by the catalogues. Also, it applies in this approach that the system requirements are sufficiently defined (I) and the system integration, verification, validation as well as the transition of the SMA+AM joint assembly is done outside of the design catalogue (IV). For example, the combination of SMA wire actuators and 3D printed carrier components results from the user's completed requirements analysis. This can be done with the support of VDI 2519 [20]. The integration and functional testing of the finally developed SMA+AM actuator system is no longer described in the catalogues (IV). Instead, the underlying VDI frameworks must be used.

The subsystems described below (II, III, V) can be processed in a simplified way with the assistance of the two catalogues and are outlined in green as well as marked with green Roman numbers. If it is clear what the requirements are for the SMA+AM joint assembly, a corresponding system architecture is set up (II), which in the simplest case consists of a mechanical and a mechatronic subsystem. This also requires appropriate modelling and analysis of the system (II). In the core variants catalogue presented in chapter 3, variants of the SMA+AM joint assemblies are presented in order to be able to make a preselection for further development of the system architectures and concepts (II). At the same time, calculation and experimental results from the solution catalogue can be used for the modelling and analysis of the system. This can be done in subsystem II. Within the implementation of the individual subsystems (III), examples form the solutions catalogue can be used for further development of the core variants. In addition, AM offers great geometric design freedom in order to ensure the best possible adapted and always flexible requirements management (V). Thus, geometric adaptations of the surrounding components can always be addressed during the development of the joint assembly.

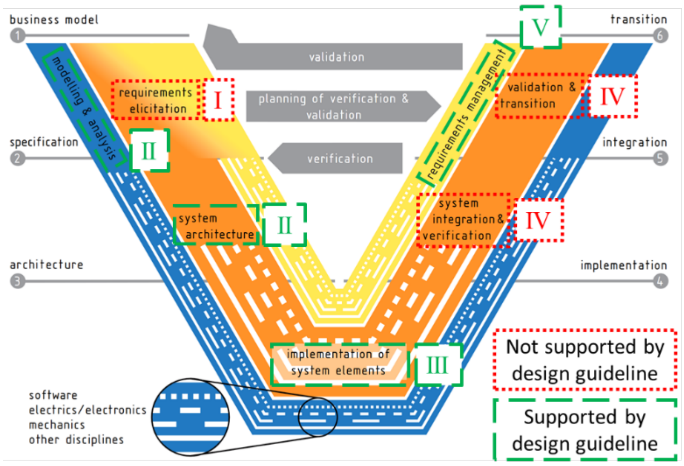


Figure 4. Integration of the design catalogues into the V-model of VDI 2206 [14]

4.2. Integration into Product Development Model (VDI 2221)

Figure 5 shows a highly simplified form of the approach to product development according to VDI 2221 [17] in order to describe the integration of the two design catalogues from chapter 3. The sub-items are described in more detail in Chapter 2.2.

The design catalogues presented in chapter 3 can be used here in analogy to VDI 2206 after the requirements and function analysis (I, II) and before elaborating the utilization as well as the product documentation (VII, VIII). This is marked with red outlines and red Roman numbers. At this point, the use of a combination of SMA wires and AM is set and basic approaches to solutions are searched for in order to develop feasible modules.

The sub-items supported by the design catalogues are marked in green with green Roman numbers. The solution approaches (III) can be found within the variants of the core

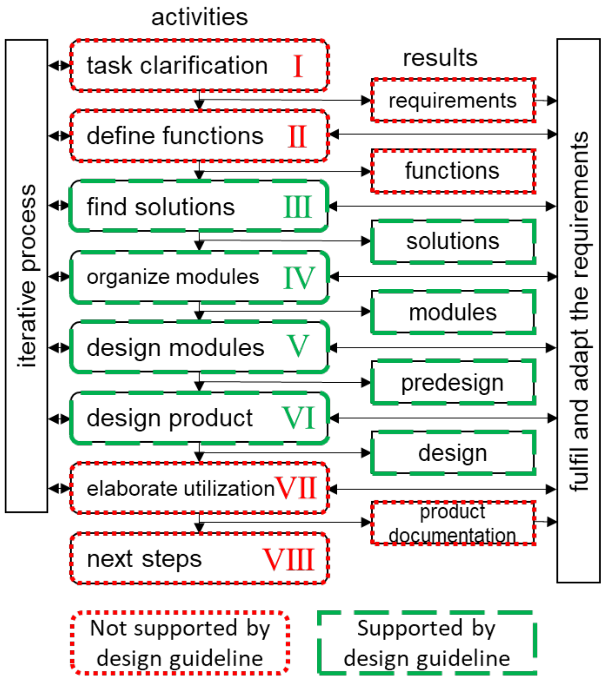


Figure 5. Integration of the design catalogues into the VDI 2221 [15]

catalogue. These solution approaches can be selected and organized for further use (IV). For the design of the individual modules (V, VI), the solution catalogue with the examples of joint assemblies and quantitative data from calculations and experiments listed therein can be used. Depending on the complexity of the SMA+AM joint assembly, it is either possible to work directly with a variant from the solutions catalogue or it is necessary to work with one of the V-models from chapter 4.1. During the creation of the modules, preliminary considerations can already be made about the manufacturing technologies of the individual parts, whereby the existing manufacturing facilities are the main criteria for exclusion. At this point in the development, it is clear which components will be manufactured additively and which conventionally. When working out the design, opportunistic [21] and restrictive [18, 22] design guidelines for the additive manufacturing of carrier components can be included with the help of the design catalogue. This is to prevent avoidable errors related to additive manufacturing in the final design. This procedure corresponds to the DfAM according to Kumke et al. [23], which can also be classified in VDI 2221.

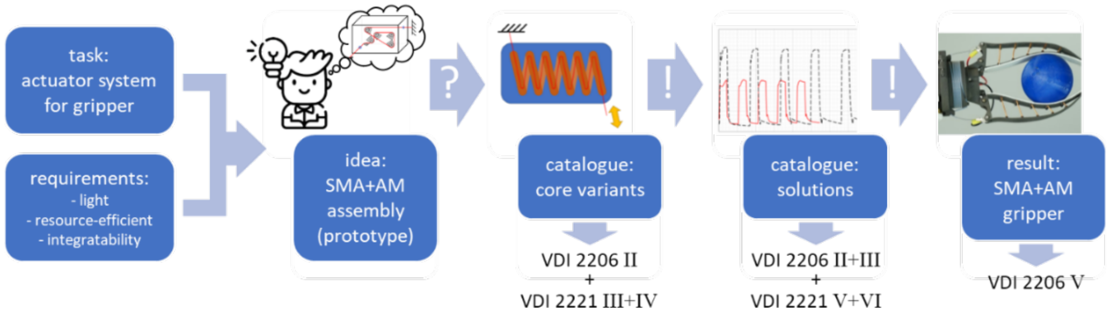


Figure 6. Example of the simplified development of an SMA+AM gripper using the guideline integrated into the VDI framework

5. Conclusion and Outlook

In this paper, a core variants catalogue as well as a solutions catalogue under development for the design of SMA+AM joint assemblies were presented, which were integrated into the existing VDI frameworks for general product development (2221) [17], mechatronic systems (2206) [16] as well as specific extensions to SMA (2248) [19] and AM (3405) [18]. During the development of the core variants catalogue, particular attention was paid to ensuring a clear structure for easy access by the user. The qualitative information on compactness, friction losses and achievable stroke, for example, helps to quickly select a core variant. The solutions catalogue was developed based on these core variants. This catalogue is under development and will contain detailed information on possible influence parameters, potentials and restrictions for all variants. Integration into the VDI framework was carried out for the necessary stages of the development. This includes finding a solution, modelling, analysing and performing the final design of the actuator assembly.

With this guideline, researcher and engineers are first given an overview of the integration possibilities of SMA wire actuators in AM-manufactured carrier components (core catalogue) and then provided with solution ideas for implementation (solutions catalogue). Figure 6 illustrates a simplified application of the catalogues, in combination with the VDI frameworks, for the development of an SMA+AM joint assembly for a gripper development.

In the future, the existing catalogues for core and solution variants will be extended by further deflection concepts and supported by analytical studies and experimental setups. In particular, the calculation of expected force and stroke losses due to friction in the deflection points and the supplementary experimental determination of the empirical data will be focussed on. A consideration of the material fatigue of the SMA wire actuators will be carried out to a limited extent, as [24] has already conducted studies in this regard.

References

[1] Kohl, M., 2002. *Entwicklung von Mikroaktoren aus Formgedächtnislegierungen.* Universität Karlsruhe (TH), Karlsruhe.

[2] Langbein, S., Czechowicz, A., 2021. *Formgedächtnistechnik: Entwickeln, Testen und Anwenden*, 2nd edn. Springer Fachmedien Wiesbaden, Wiesbaden.

[3] Janocha, H., 2007. *Adaptronics and Smart Structures: Basics, Materials, Design, and Applications*, 2nd edn. Springer Berlin Heidelberg, Berlin, Heidelberg.

[4] Mohd Jani, J., Leary, M., Subic, A., Gibson, M.A., 2014. A review of shape memory alloy research, applications and opportunities, in *Materials and Design 56*, p. 1078.

[5] Stoeckel, D., 1990. Shape memory actuators for automotive applications, in *Materials and Design 11*, p. 302.

[6] Motzki, P., Seelecke, S., 2019. Industrial Applications for Shape Memory Alloys, in *Reference Module in Materials Science and Materials Engineering 4*, p. 254.

[7] Furst, S.J., Bunget, G., Seelecke, S. Design and fabrication of a bat-inspired flapping-flight platform using shape memory alloy muscles and joints, in *Smart Materials and Structures 22*, p. 14011.

[8] Simone, F., Rizzello, G., Seelecke, S., 2017. Metal muscles and nerves - A self-sensing SMA-actuated hand concept, in *Smart Materials and Structures 26*.

[9] Löffler, R., Rücker, D., Müller, F., Hornfeck, R., 2021. Method for simulative reproduction, verification and technical adaptation as part of biological kinematics studies, in *Procedia CIRP 100*, p. 649.

[10] Dynalloy Inc. Technical Characteristics of Flexinol Actuator Wires. http://www.dynalloy.com/pdfs/TCF1140.pdf. Accessed 6 Dec. 2022.

[11] Motzki P., Kunze J., York A., Seelecke S., 2016. Energy-efficient SMA Vacuum Gripper System, in *ACTUATOR 16 - 15th International Conference on New Actuators*, p. 526.

[12] Bunget, G., Seelecke, S., 2010. BATMAV: a 2-DOF bio-inspired flapping flight platform, in *Active and Passive Smart Structures and Integrated Systems 7643*, SPIE, p. 1.

[13] Demoly, F., Dunn, M.L., Wood, K.L., Qi, H.J. et al., 2021. The status, barriers, challenges, and future in design for 4D printing, in *Materials and Design 212*, p. 110193.

[14] Kang, M., Pyo, Y., Jang, J.y., Park, Y. et al. Design of a shape memory composite (SMC) using 4D printing technology, in *Sensors and Actuators A: Physical 283*, p. 187.

[15] Lu, H.Z., Yang, C., Luo, X., Ma, H.W. et al. Ultrahigh-performance TiNi shape memory alloy by 4D printing, in *Materials Science and Engineering: A 763*, p. 138166.

[16] Verein Deutscher Ingenieure. *VDI 2206 Development of mechatronic and cyber-physical systems*, Berlin. Beuth Verlag, 2021.

[17] Verein Deutscher Ingenieure. *VDI 2221 Design of technical products and systems Model of product design*, Berlin. Beuth Verlag, 2019.

[18] Verein Deutscher Ingenieure. *VDI 3405 Additive manufacturing processes Design rules for part production using material extrusion processes*, Berlin. Beuth Verlag, 2021.

[19] Verein Deutscher Ingenieure. *VDI 2248 Product development using shape memory alloys (SMA): Basics and application examples*, Berlin. Beuth Verlag, 2019.

[20] Verein Deutscher Ingenieure. *VDI 2519 Procedures for the compilation of tender and performance specifications*, Berlin. Beuth Verlag, 2001.

[21] Bin Maidin, S., Campbell, I., Pei, E., 2012. Development of a design feature database to support design for additive manufacturing, in *Assembly Automation 32*, p. 235.

[22] Redwood, B., Garrett, B., Schöffer, F., 2017. *The 3D printing handbook: Technologies, design and applications*. 3D Hubs, Amsterdam.

[23] Kumke, M., Watschke, H., Vietor, T., 2016. A new methodological framework for design for additive manufacturing, in *Virtual and Physical Prototyping 11*, p. 3.

[24] Meier, H., Czechowicz, A., 2012. Computer-Aided Development and Simulation Tools for Shape-Memory Actuators, in *Metallurgical and Materials Transactions 43*, p. 2882.