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Maintenance of Shape Memory Actuator Systems - Applications, Processes and Business Models

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Abstract

Today products are more and more substitutable due to progress in information technology as well as globalization. New competitors, particularly from developing and emerging countries are putting established companies under pressure, due to lower production costs. In consequence, the prices and thus realizable profits for companies are decreasing. Focusing on the customer value can help to break this trend. In this way, the product understanding is changing. Besides offering products, offering services and combining both is getting more and more important. However, the product requirements are changing and may require new technologies. For small-to-medium-sized actuator applications shape memory alloy based actuator systems are a promising technology. In addition to the advantages in physical and mechanical properties, the integrated sensor function allows a simple condition monitoring and thus easy maintenance processes. Companies can generate new value for customers and are therefore able to improve their competitiveness. The consequence is that companies are offering new business models. For this reason, these actuators are ideal for industrial product-service systems. This paper illustrates the maintenance processes of shape memory based actuator systems using the integrated sensor function. Based on these maintenance processes and suitable business models are designed as well as analyzed. As a result, recommendations for these actuator systems are provided. It is vital to introduce the relevant areas like shape memory alloy based actuator systems, industrial product service systems, maintenance and business models in the field of mechanical engineering first.

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Keywords: business model; maintenance; product-service system; process; shape memory alloy

1. Introduction

In today's industry, products are evaluated mostly based on their technical properties. Therefore, products are easy to replace and thus decrease the competitiveness in the long run. In this case, competition focuses almost exclusively on cost. The combination of goods and services allows a differentiation from competition. This makes it possible to reduce the importance of cost as criteria for competition. Nevertheless, it must be taken into account that new technologies may be required to provide IPSS. In the field of small to medium sized actuator applications, shape memory alloy based actuator systems are a promising technology that allow very simple actuator-sensor systems by which companies are able to offer IPSS. Besides advantageous physical and mechanical properties of shape memory alloys (SMAs), previous works have already shown that SMAs have high potential for services [1]. The integrated sensor function or self-sensing of shape memory alloy based actuator systems (SMA-ASs) allows a statement about proper functioning [2] and is capable to provide a condition monitoring of the actuator system [1]. Regardless, investigations on SMAs mainly focus on material, mechanical and control aspects. An evaluation of the service potential based on the material properties of SMAs is missing, as well as investigation of proper processes and discussion of these. Therefore, the purpose of this paper is to develop maintenance processes, which take into account the specific features of SMAs. Additionally, proper business models are discussed, which use these maintenance processes.

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The paper is organized as follows: Section 1 gives an overview on the application of SMA-ASs, discusses industrial product-service systems (IPSS) from a literature perspective. Due to its relevance for IPSS, an overview of maintenance is given. Finally, different types of business models in the field of mechanical engineering are presented. In section 2, maintenance processes of SMA-AS are illustrated with the distinction between a functional and availability-oriented usage of these actuator systems. Section 3 focuses on the resulting business models for SMA-AS, which can be derived from the maintenance processes. In section 4, the recommendation for companies in the context of SMA-AS are discussed. Finally section 5 draws a conclusion and provides an outlook.

Nomenclature

BM	Business model
CRM	Customer relationship management
IPSS	Industrial product-service system
KAM	Key account management
PLM	Product lifecycle management
SMA	Shape memory alloy
SMA-AS	Shape memory alloy based actuator system

1.1. Application of shape memory alloy based actuator systems

New materials such as smart materials enable innovative solutions for various applications. Noteworthy in this field are SMA. SMAs have the astonishing ability to remember their original shape, have an actuator function and can show super elastic behavior. They are characterized by high displacement and forces, high corrosion resistance, and good biocompatibility [3, 4, 5]. Furthermore, SMAs have an integrated sensor function or self-sensing function, which can be used for the control of purposes. [6] Regarding the positioning of SMA actuators, various studies prove this ability [2, 6, 7, 8, 9]. Additionally, Czechowicz [10] concludes that by measuring the resistance of the material, monitoring of fatigue is possible. One important feature of SMA compared to conventional materials is monitoring of fatigue and monitoring of functionality by measuring the displacement. By measuring resistance, conclusions about material condition and material history as well as displacement can be made. Thus, countermeasures can be taken, if the resistance decreases below a certain value and possible breakdowns of the system prevented.

Due to the special sensor properties of SMAs, there is a high potential for a simplified maintenance of these actuators or rather a function ensured by these actuators. This can also help to reduce the complexity of technical solutions.

SMA-ASs are mechatronic actuator systems, which in the simplest case are composed only of a SMA-Actuator. When requirements for control exist, a board is added. If information about fatigue and functionality are monitored based on the sensor characteristics, the board is replaced by a microcontroller. This has interfaces for information processing such as Ethernet or bus interface. Then software is used for information processing and evaluation as last part of a SMA-AS.

For this reason, SMAs are interesting for a wide range of applications, especially valves, locking and unlocking mechanisms or vibration damping applications [3, 11]. Additionally, if the knowledge of the state of an actuator is relevant as well as the complexity and compactness of the actuator system is critical, the use of SMAs is promising almost industry independent. Figure 1 illustrates the wide range of actuator applications, ranging from biomedical applications to telecommunication.

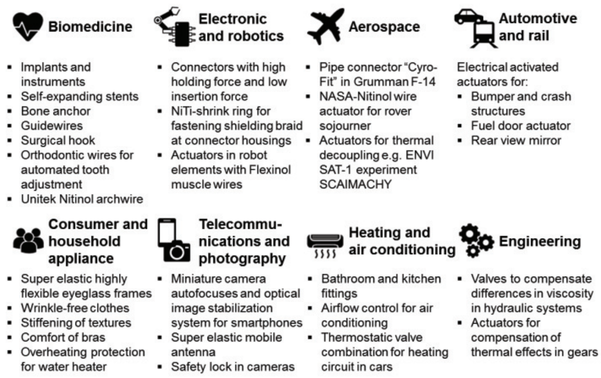

Figure 1: Applications of shape memory alloy based actuators

1.2. Industrial product-service systems

In literature, there are various terms for IPSS, like extended products, product-service system, service engineering, which are all very similar [12]. Rese et al [13] state that IPSS integrate products and services with the goal to create value beyond the value of a single product. Furthermore, their integrated and mutually dependent process of planning, developing as well as delivering goods and services is a unique feature of IPSS. This applies to the entire IPSS life-cycle. To offer IPSS, it is of vital importance to include the customer.

Companies often limit themselves to products and rarely consider the potential of services. According to Meier and Uhlmann [14], service potentials in the field of mechanical engineering are, among others, financing, training, certification, quality assurance, simulation and availability as well as maintenance.

1.3. Maintenance

The high importance of maintenance for companies can be illustrated by their average annual expense. Based on a study of the VDMA [15], the average expense for maintenance is about 4.7 percent of the replacement costs of an investment, which represents - over a lifetime of 20 years - the value for the machine investment.

Maintenance is defined as a combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function [16]. The goals of maintenance are to ensure the availability, safety, impact on the environment and to uphold the durability of the item to function at lowest costs [16]. Figure 2 illustrates the components of maintenance according to DIN 31051 [17].

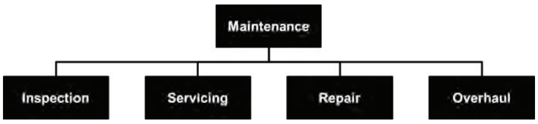

Figure 2: Components of maintenance [17]

1.4. Business models in the field of industrial product-service systems

For the later discussion of appropriate characteristics of business models for the presented maintenance concepts of shape memory alloy based actuator systems (SMA-AS), it is necessary to briefly introduce the relevant terms.

There is no generally applicable definition of the term business model (BM) in academics or business [18, 19]. Within a BM, the focus is on the customer as the company and their business partners create the customer value, which lead to sufficient revenues. Besides that, BMs allow companies to differentiate themselves from their competition and to create competitive advantages. [20] The key elements of a BM are as follows [13]:

- *Value proposition* covers the value delivered to the customer.
- The *Architecture of value* captures information about the solution. The value architecture can be a product, a service or a combination of both.
- *Customer* describes features about the customer like the geographic scope or characteristics, e.g. the area of business, purchasing power, etc.
- *Revenue model* refers to the types of revenues gained. The revenue stream can be based on the order, based on the availability or based on the result.

Business models for products or services are product-oriented. In this BM, the customer buys a product from the provider. The customer is responsible for operation and everything else like maintenance. The revenue stream is based on the order, which is initiated by the customer.

In the field of IPSS, business models are typically function-oriented, availability-oriented or result-oriented. In a function-oriented BM, the IPSS provider performs maintenance on the customer's request. The logical development is the result-oriented BM. In this, the provider is fully responsible.

The responsibility for operation changes more and more from the customer to the IPSS provider. In consequence, the organizational challenges increase for the provider. This goes hand in hand with change in the revenue model. The revenue coverts from transaction dependent ones in case of function-oriented BM to transaction independent ones in case of availability- or result-oriented BM. Figure 3 sums up the main characteristics of products, services and industrial product-services systems regarding business models and the respective revenue stream.

	Product-oriented	Function-oriented	Availability-oriented	Result-oriented
Responsibility for production	Customer	Customer	Customer	Provider
Provision of operating personnel	Customer	Customer	Customer	Provider
Property	Customer	Customer	Customer/ provider	Provider
Initiation of service	Customer	Customer	Provider	Provider
Provision of service personnel	Customer	Customer/ provider	Provider	Provider
Revenue model	Payment based on order	Payment based on order	Payment based on availability	Payment based on result
Example	e.g. investment good	e.g. investment good + maintenance contract	e.g. investment good + availability guarantee	e.g. Operation of investment good and guarantee of

Individualization
Complexity of architecture of value
Potentials to generate value (for the customer)

Figure 3: Characteristic of products, services and industrial product-service systems regarding revenue model [14, 21]

Depending on the focus, there are other important elements. For a later discussion, the strategy, contract, risk and network play a major role. For the latter, the types of optimization network, project network, evolution network and fusion are used. [22]

2. Maintenance processes for SMA actuator systems

Like all technical products, SMA-AS need maintenance somehow. Normally small actuator systems are not condition-monitored because the costs of these components are in no relation to the value of the actuator system. Through the sensor characteristics, SMA-AS can substitute conventional actuator systems because of their simple structure. Condition monitoring is now possible for a variety of applications where the technical requirements of the application are in line with the characteristics of SMAs. This allows availability- or result-oriented IPSS even for simple systems. An SMA-AS with condition monitoring feature consists of the actuator, electronics like a microcontroller, data about the condition of the system, a data interface for exchanging information and proper software.

The aim is to create a maintenance concept for SMA-AS in way to ensure the function provided by the SMA-AS and to minimize breakdown. In figure 4, two maintenance concepts for SMA-AS are presented. The left one is a function-oriented approach against which the right one is the availability-oriented approach. For both, all components have to be configured appropriately so that the condition monitoring works. First, the *function-oriented maintenance approach (left)* is described. After the SMA-AS provider has made the system ready to use for the customer, the customer is responsible for the operation. The SMA-AS by itself measures the resistance at every activation. The measured resistance is saved and compared to the last two resistances. The critical indicator for a breakdown of an SMA-AS is the change in resistance behavior. If the resistance behavior changes from linear to a non-linear

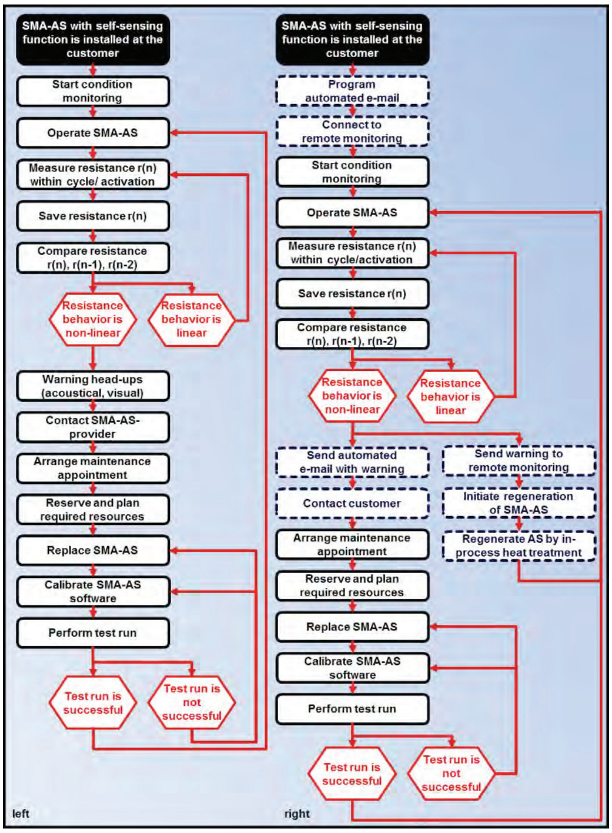

Figure 4: Maintenance concepts for SMA-AS

behavior, the breakdown of the system will happen in less than 2,000 activations, as the experiments have indicated. However, this is enough to react. An acoustical or visual (light) signal will warn the customer. The customer has to contact the SMA-AS provider to arrange a maintenance appointment. The SMA-AS provider has to plan the required material and personnel resources. At the appointment, the service staff of the SMA-AS provider will replace the SMA-AS. Due to the sensitivity of the SMAs, calibrating the SMA-AS software is needed. Finally, a test run is performed. A new maintenance will only be triggered again as soon as the resistance behavior has changed.

The *availability-oriented maintenance approach (right)* is based on the same technical system. To clearly illustrate changes, these are marked in blue dashed lines.

Due to the change in responsibilities from the customer to the SMA-AS provider for operation automated e-mail and a connection with remote monitoring at the SMA-AS provider has to be set up. The e-mail is later used to send the warning to the SMA-AS provider. The remote monitoring is important to state information on the SMA-AS at any time. When the resistance behavior changes, an automated e-mail is generated and sent to the SMA-AS provider. The SMA-AS provider will contact the customer and arrange an appointment, plan the required resources and maintain the SMA-AS.

Alternatively, there is the possibility to regenerate an SMA-AS without replacing the SMA actuator. In this case, the warning is sent to the remote monitoring which initiates the regeneration of SMA-AS. After the regeneration, the SMA-AS operates while measuring the resistance. The resistance is compared and in case the resistance behavior is not sufficient directly after the regeneration, the automated e-mail initiates maintenance with replacement.

Although this approach is promising, there is still a considerable need for research. It must be investigated what effects can be realized and what adjustments are required to the system as a whole in order to do the above. It is anticipated that regeneration cannot be repeated endlessly and the actuator system still needs to be replaced at some point. However, the maintenance interval could be extended.

3. Components of business models for shape memory actuator systems

Figure 5 sums up components for different business models of SMA-AS that are possible through the use of self-sensing. The key elements of a BM are marked in black (see also section

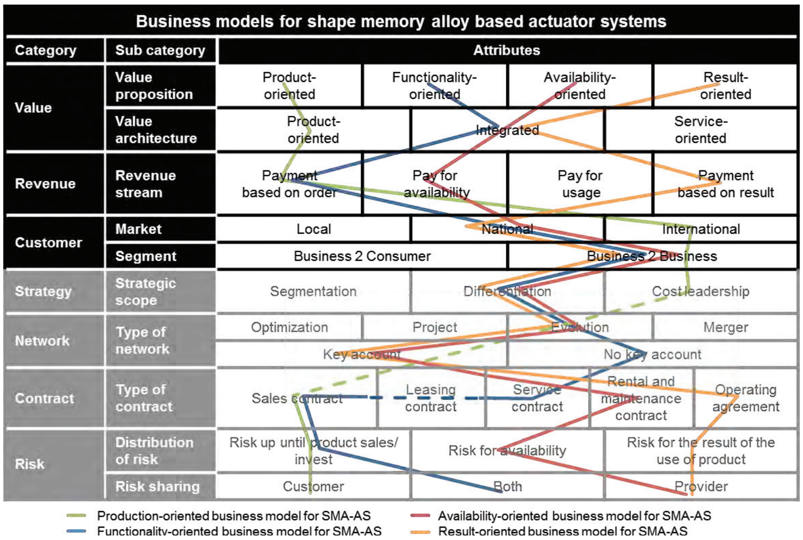

Figure 5: Components of business models for shape memory alloy based actuator systems

1.4); other elements are highlighted in grey. The lines in Figure 5 illustrate the most favorable attributes of the business models.

First, there is the traditional *product-oriented business model*. The value for the customer is generated by offering a technical solution with advantageous properties, which is capable of using condition monitoring. To use the condition monitoring, the customer has to set up the program, software and process by himself. The strategic scope is cost leadership due to limited value beyond the technical product. An international market is essential to reach high volumes. A network is not applicable, because of limited value added.

Particularly interesting for SMA-AS are function-oriented or availability-oriented business models. In a *function-oriented business model* the value is generated by a low downtime of the SMA-AS by using condition monitoring. The customer closes when purchasing a service contract. Nevertheless, revenues are still transaction based because the customer has to order the service. The strategic scope of this BM is differentiation. A key account manager is not required due to a lack of standardization of SMA-AS but can make sense for the SMA-AS provider to increase customer loyalty even more. Contract types can range from leasing to service contract or rental or maintenance contract, depending on the needs of the customer.

In an *availability-oriented business model*, value is generated by guaranteeing a determined availability for the customer, which minimizes his risk and allows the outsourcing of processes. In contrast to the previous BM, revenues can be independent from the transaction based on availability, which leads to a more stable cash flow. For this BM, it is vital to have a key account, which is responsible for the communication with the customer. The risk is borne almost exclusively by the SMA-AS provider. Contract types are ranging from service contract to rental or maintenance contract as well as operating agreement depending on the requested ownership by the customer.

Finally, a *result-oriented business model* is possible. In this model, the processes and risk are totally outsourced. Revenue is based on result or activation. The result-oriented BM is equal to an operation model, which is financed on a pay-per-production basis. [14] This BM has a huge potential in the production environment.

Nevertheless, the importance of result-oriented business model is low, because it is almost exclusively a subcomponent, which can provide a function like thermal control of components. Therefore with SMA-AS alone no result-oriented BM are possible. In a result-oriented BM SMA-ASs are only subcomponent. However, SMA-AS can be part of a complex system like a production line and then be part of a result oriented BM. A result-oriented business model based on SMA-ASs is discussed in [20].

4. Recommendation for companies

Because of the presented BMs and current market structure in the field of SMAs and mechanical engineering, some recommendations shall be made. They can be subdivided into technology, strategic value added network, key account management (KAM), customer relationship management (CRM), product lifecycle management system (PLM-System), contracts and changes in marketing approaches.

Nowadays, applications of SMA-AS are almost exclusively in niche with small volume. Therefore, components of SMA-ASs are only limited offered by companies and thus available. As a result, integration of these components like software, hardware, especially the microcontroller and the relevant interfaces have to be carried out by the users. Regardless, integration is critical to add value for the customer and be able to successfully offer IPSS based on SMA-AS.

The lack of standardization in the field of SMAs regarding material standards, development guidelines or handling leads to high resource requirements. In addition, the market structure in the field of SMAs is characterized by a high degree of fragmentation besides a few large-sized enterprises. Nevertheless positioning on single steps of the value chain for SME is promising, if the SME is highly specialized in components of the SMA-AS. Companies which are active in the field of SMAs or want to become active should extend their competence and build trust with potential partners starting with project *networks*. Later types of networks are evolution networks or on long-term a merger of the involved partners.

To create customer value, the exact knowledge about customer needs is essential. For this reason, it is necessary to establish a *key account management or customer relationship management* that is the one point of contact and one-face-to-the-customer for the customer. The KAM should be responsible for coordinating all activities of a company or network. The CRM should evaluate the information of the SMA-AS and important customer data. Moreover, it should be capable to identify the customer needs and to consider them in service delivery. In this context, the knowledge of the customer processes is critical.

The large number of information required and involved functions or business partners to provide services requires efficient processes that prevent redundancy among others. To have efficient internal processes and be able to provide customized solutions, a *PLM* is required. Since the data for these SMA-AS are sensible, cross company data exchange requires a high level of trust between business partners.

Regarding *contracts,* it has to be distinguished between contracts with the customer and contracts with business partners. For both types of contract the following points have to be carefully defined: responsibilities and liabilities, risk distribution as well as duration. In addition, for other business partners, knowledge sharing, revenue distribution, rules for new network partners as well as contractual penalties need to be considered.

Finally, a change in the marketing approach is recommended. The four Ps (Price, Place, Product, Promotion) should be expanded to seven Ps including physical facilities, personal and process management. The last three Ps are suitable for services. [23] This last three Ps focus on major components for the creation of customer value and for providing a solution. Personnel, for example, emphasizes the importance of customer support by the key account manager, and process management considers the importance of processes in delivering the solution.

5. Conclusion and Outlook

The paper has highlighted maintenance processes to provide various business models based on simple SMA-AS. SMA-AS can help companies to offer industrial product-service systems and thus be able to differentiate themselves from competition. Currently, SMAs are very knowledge-intensive due to a lack in standardization and the low level of awareness. This leads to high resource requirements. For companies with experience in the field of SMAs, this is an advantage over the competition, as this is a crucial market entry barrier. Regardless of the level of experience of a company with SMAs, the market structure probably requires cooperation between companies, if IPSS are offered, which are based on SMAs.

Although the processes shown have been developed and tested by a demonstration system, further studies are needed. In particular, further studies should focus on the predictability of fatigue and the functionality of the self-sensing for various parameters like various wires or heat treatments. Investigations should be done about the ability of regeneration of SMAs. In this context, requirements and limitations are of high interest. Furthermore, the development of low-cost electronics, which has only the required interfaces can lower costs and thus expand the possible applications. Of course, a long-term test of SMA-AS under real conditions is necessary.

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