Experimental Validation of Condition Monitoring for Electrically Activated Shape Memory Alloys for an Unlocking Device

Christian Rathmann, Benedict Theren, Benjamin Fleckoz, Bernd Kuhlenkötter
Ruhr-University of Bochum, Universitätsstraße 150, 44801 Bochum, Germany
Email: rathmann@lps.rub.de; theren@lps.rub.de; fleckoz@lps.rub.de; kuhlenkoetter@lps.rub.de;

Abstract. Shape memory alloys (SMA) belong to the group functional materials which can be activated thermally. Along with a phase transformation, they can remember a previously imprinted shape and have a special resistance behavior. Therefore, they can also be used as a sensor and may be capable of detecting various system states in technical systems. This paper makes a contribution by evaluating the measurability of measured variables by SMA elements. Furthermore, it investigates the technically relevant states of “blockade” and “activation” of electrically activated shape memory actuators. It develops and validates an algorithm which is able to detect a possible “blockade”. Moreover, this work presents a hardware concept for a condition monitoring system of shape memory actuators.

1. Introduction
The electrical activation of SMA actuators has several advantages compared to conventional actuators, e.g. reduced space or simple methods to monitor the system [1]. Evaluating experimental data has revealed that there is a high dependency of the electrical resistance or current as well as specific actuator states such as the remaining lifetime [2], elongation [3], stress [4], temperature [3][5] or blockage [6]. By condition monitoring it is possible to provide recommendations for action in case an error is detected [7]-[9]. The following study develops a condition monitoring for the actuator state “blocked” as well as a proper “activation” in order to give specific recommendations regarding the SMA actuator system.

1.1. Structure
Preliminary different measurands are classified regarding their ability to be monitored by an SMA element. Based on this classification, specific actuator errors are assigned to certain measurands. A fault tree analysis is performed in order to derive certain recommendations for the representative actuator state “blocked”. A series of experiments are performed in order to find a specific criterion to differ a blocked actuator from a fully activated one.
After evaluating the data, an algorithm is derived which is able to detect the blockage of an SMA actuator. Finally, this work develops a physical condition monitoring system with a Raspberry Pi.

2. Available Measurands and Status Detection with SMA
All measurands are grouped according to [8]-[13] and presented in Figure 1. Based on the results taken from the publications of [3][5][6][14] and experience, a qualitative assessment is performed if
SMA elements are capable to measure the specific measurands. Through measuring variables it is possible to formulate statements concerning the monitoring of system states. Consequently, this leads to a certain system intelligence. Mechanical variables are generally measurable except for torque and rotational speed. Torque can only be applied for small ranges and rotational speed is not detectable. Process variables such as the number of produced goods or quality are measurable indirectly through SMA elements. Regarding the number of produced goods, the number of activations of the SMA element is an indicator. Information on the product quality can be gathered if the quality characteristic depends on the proper closing or opening of the SMA actuator. The thermal sensitivity of SMA elements makes them suitable for measuring thermal variables especially during the phase transformation. Electric measurands are easy to access during the electrical activation. However, it is not advantageous to exclusively use them as a sensor for measuring electrical variables. Fluidic variables can be measured by using an SMA sensor element, as shown on the basis of fluid velocity [14]. Therefore, it is possible to measure e.g. the flow rate and loss.

| measurand | SMA | s | a/s |
|-----------|-----|---|-----|
| mechanical | force and pressure | ++ | ++ |
| stress | ++ | ++ |
| velocity | o | ++ |
| torque | o | o |
| speed of rotation | n.d. | n.d. |

| measurand | SMA | s | a/s |
|-----------|-----|---|-----|
| fluidic | throughput | ++ | + |
| fluid loss quantity | ++ | + |
| pressure change | o | + |
| fluid level | n.u. | n.u. |
| humidity | n.d. | n.d. |

| geometric | length, displacement | + | ++ |
| clear | + | |
| thickness | n.u. | n.u. |
| angle | o | o |

| material changes | change of shape | n.d. | ++ |
| corrosion | n.d. | n.d. |
| temperature | o | + |
| mechanical | + | ++ |
| thermal | o | + |
| environmental | n.d. | n.d. |

| optical | color, texture, reflection, pattern | n.d. | n.d. |
| electrical | substance properties, impurities | n.d. | n.d. |

Figure 1. Overview of the detectable states of SMA actuators and SMA sensors.

3. Condition Monitoring with a Binary Moving SMA Actuator
The state of the actuator “blocked” is further analyzed by using a fault tree analysis. This is presented in figure 2. Different reasons for the error are summarized. The main triggers leading to a functional failure are blockage and the lack of performance of the SMA actuator system. In the event of a loss of function due to a lack of performance of the SMA actuator, relevant aspects to be considered are SMA-unspecific events like damaged reset elements as well as material-specific events like material fatigue. The functional and structural fatigue can both be detected by the electrical resistance. Therefore, it is possible to predict the time until the required displacement cannot be reached. The other trigger blockage is particularly interesting because it directly indicates a faulty operation and thus should be prevented or at least easy to detect.
It is assumed that by changing the electrical resistance during the phase transformation it is possible to detect blockage if it occurs [6]. As it is possible to evaluate blockage, the functionality of the actuator system can be evaluated after each activation. In case of such an event, it is recommended to perform the next activation with reduced energy in order to validate the sustainability of the error. If the blockage still exists, it is possible to initiate countermeasures. However, there has not been any reliable investigation which directly focuses the blockage of an SMA actuator system. To validate the state and fault detection with SMAs, further experiments are required for its validation. For this purpose, the case of blockade is examined more closely in the following paragraph.

![Figure 2. System states and faults of a binary SMA actuator system.](image)

### 4. Material and Methods

#### 4.1. Experimental Setup and Material

The series of experiments are performed in order to propose a model for the blockade detection of an SMA actuator. Smartflex90 from SAES Getters are used as samples. When the wires are activated, the electrical voltage is controlled. Therefore, the current arises out of voltage. For this reason, this analysis uses the current instead of the electrical resistance. The analyzed SMA actuator wire should show significant differences in its behavior of the electrical current if it is blocked compared to a regular activation. Figure 3 shows the experimental setup for this study.

The sample is mounted between an isolating layer and a copper block. This minimizes the electrical resistivity. The blocking of the wire is performed by a firm connection of the lower specimen mounting and the test frame. A blocking of the wire is defined as a reduction of the wire’s movement by 90%. A complete activation is defined as a movement of 4 mm or more. All required experimental parameters are summed in figure 3. 16 wires in total are blocked five times and each wire is activated 70 times. The newly mounted samples are activated 30 times at the beginning of the measurement. Afterwards they are blocked once and activated ten times. This cycle is performed five times.

Figure 4 presents the current-time diagrams for an activated (left) and a blocked (right) SMA wire. For a better overview, the scale is fitted to the relevant area. The current is scattered on purpose. The
higher current leads to a higher wire movement and allows an analysis of blocking at these movement levels. The range of the movement is from 4 mm to 6 mm. Significant differences in the current-time plots can be identified both by a qualitative analysis of the plot’s trend and by a quantitative analysis of the current’s level. The activated wire follows a rather cubic trend while the blocked trend can be described as rather squared. For the activated wire the current’s level in the beginning of the activation process is higher than in its end. For the blocked wire, the levels vary inversely to the trend of the activated wire (See table 1).

**Figure 3.** Experimental setup and parameters.

**Figure 4.** 2 current time plot of an activated SMA wire (left) and a blocked SMA wire (right).

5. Results
For a data analysis, a test algorithm is derived in order to distinguish blocking from activation. The process is shown in Figure 5.

The criterion “higher than 250 mA” is chosen to make a clear difference between the beginning of the activation and measurement noises. The value is based on experience and is specifically chosen for a
wire diameter of 0.5 mm. The power source delivers its electrical output after 1 ms. By a measure frequency of 50 Hz, this leads to five values until the required values are reached. In order to increase the reliability, this value was set to ten.

The algorithm is used for 80 data sets of a blocked and for 80 data sets of an activated wire. One activation and one blocking are wrongly detected. The false detected activation leads back to a lack of movement. The minimum movement is set to 4 mm but due to a deterioration, the sample movement decreased to 3.5 mm. In conclusion, the criterion “complete activation” is not met. The wrongly detected block is located in an insufficiently installed blocking tool. This causes a reduction of movement by just 80% instead of the required 90%. This makes this variation to an outlier and it will not be further regarded.

It has been possible to detect a total of 100% of the blockings and 98.6% of the activation. This leads to the conclusion that the algorithm works properly.

![Figure 5](image)

**Figure 5.** Test algorithm for condition monitoring of a blocked SMA wire.

**Table 1.** Differences depending on the actuator state.

| actuator state | activated wire | blocked wire |
|----------------|----------------|--------------|
| lower current at beginning of activation compared to end | higher current at beginning of activation compared to end | roughly cubic trend | roughly square trend |

6. **Concept of a Condition Monitoring System for Electrically Activated SMA Actuator Systems operating binary**

Setting up a condition monitoring system requires further components such as a sensor to acquire current and voltage. The sensor sends its signal to a microcontroller with enough power for data processing and saving as well as an Ethernet or Wi-Fi connection to send out messages in case of detected errors. In this case a raspberry is chosen. For a prototype, the LMP92064 by Texas Instrument is used as a sensor. It delivers its data via an SPI Interface. The most fitting micro controller is a raspberry pi because it combines all requirements and is an open source system. Figure 6 shows the circuit diagram.
Figure 6. Overview of the hardware concept of an SMA actuator condition monitoring system.

This concept can be seen as a hardware concept of [15][16]. The reliability of SMA actuators is increased by the more precise surveillance of system states. This decreases failure and, in consequence, the availability of technical systems which rely on the usage of SMA actuators.

7. Conclusion and Outlook
The paper has evaluated the possibility of using SMA elements as a sensor for acquiring different measure variables. As a result, it has been possible to prove that SMAs are well suited to measure especially mechanical, processual or fluidic variables and to be used as an actuator sensor system to detect errors and states. This work has examined how to detect the blockade of an operating SMA actuator system. Moreover, an algorithm for this purpose has been developed and validated. In conclusion, the approach to develop a condition monitoring system for SMA actuators is a promising field of research. This also increases the possible applications, which, however, will also require new business models.

7.1. Outlook
To put sensoring and condition monitoring with SMAs into practice, more research is needed. Further studies should focus on other faults and states than those presented in this paper. Additionally, it is necessary to investigate the extent to which factors such as environmental issues or actuator-specific factors influence the possibility of error detection. Furthermore, investigations are required to develop proper electronics which are customized to the needs of SMAs. These electronics have to consider the requirements of SMAs and should realize low-cost condition monitoring solutions. Finally, it will be necessary to run a long-term test of SMA actuator systems under real conditions.

8. Acknowledgment
The authors acknowledge the funding of the FLAAI project through the aviation research program LuFo V-1 by the Federal Ministry of Economic Affairs and Energy.

9. References
[1] Butera, F.; Coda, A.; Vergani G. (2007): Shape memory actuators for automotive applications. In: Nanote IT newsletter 2007, S. 12–16, revised 07.03.2017.
[2] Rathmann C, Fleczok B and Kreimeier D (2015a) An investigation using self-sensing to estimate the lifetime of shape memory actuators. In: Proceedings of the SICASE 2015 Seoul International Conference on Applied Science.
[3] Zhang JJ, Yin YH and Zhu J-Y (2013) Electrical resistivity-based study of self-sensing properties for shape memory alloy-actuated artificial muscle. Sensors (Basel, Switzerland) 13(10): 12958–12974.
[4] Lan CC and Fan CH (2010) An accurate self-sensing method for the control of shape memory alloy actuated flexures. Sensors and Actuators A: Physical 163(1): 323–332.
[5] Novák V, Šittner P, Dayananda GN, Braz-Fernandes FM and Mahesh KK (2008) Electric resistance variation of NiTi shape memory alloy wires in thermomechanical tests: Experiments and simulation. Materials Science and Engineering: A 481-482: 127–133.

[6] Herrera GA, McKnight GP, Gao X, Johnson N and Browne AL (2011) Use of intrinsic electrical resistance changes in shape memory alloys as robust actuator state and fault detection sensors. In: Proceedings of the SMASIS 2011 Conference on Smart Materials, Adaptive Structures and Intelligent Systems. New York: ASME Digital Collection, pp. 133–138.

[7] Davies A (2012) Handbook of Condition Monitoring: Techniques and Methodology. Dordrecht: Springer Netherlands.

[8] Klein U (2008) evaluation regarding vibration diagnosis of machinery. Düsseldorf: Verl. Stahleisen.

[9] VDI-Society of Production and logistics(1999) Condition Monitoring Beuth 03.080.10(2888).

[10] Czichos, H. (2015): Mechatronik. Grundlagen und Anwendungen technischer Systeme. 3., überarb. u. erw. Auflage. Wiesbaden: Vieweg +Teubner.

[11] Hering E and Schönfelder G (2012) Sensors in Science and Technics: Functionality and field of use. Wiesbaden: Vieweg +Teubner.

[12] Hesse S and Schnell G (2014) Sensors for Process and Fabrication automation: Function, Execution and application. Wiesbaden: Springer Vieweg.

[13] Standards committee acoustics, noise canceling and vibration technics (2011) Condition Monitoring and Diagnosis of machinery – general usage: Beuth 25.020(17359).

[14] Seelecke S (2015) Sensing Properties of SMA Actuators and Sensorless Control. In: Czechowicz A and Langbein S (eds) Shape Memory Alloy Valves: Basics, Potentials, Design. Cham, s.l.: Springer International Publishing, pp. 73–87.

[15] Rathmann C, Remmetz T and Kreimeier D (2015b) Maintenance of Shape Memory Actuator Systems - Applications, Processes and Business Models. Procedia CIRP 30: 84–89.

[16] Rathmann C, Czechowicz A and Meier H (2013) An Investigation of Service-Oriented Shape Memory Actuator Systems for Resource Efficiency. In: Proceedings of the SMASIS 2013 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, pp. V001T04A006.