Model-based Position Control of Shape Memory Alloy Actuators

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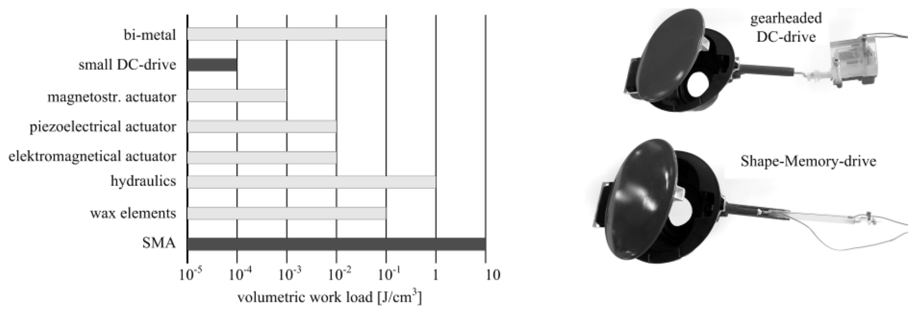
ABSTRACT

Shape-memory-alloys (SMAs) are easy to integrate into mechanical structures and capable of handling high specific workloads. Therefore, SMAs possess an outstanding potential to serve as positioning devices in various applications. We present here the multi-domain modelling of an electrically heated SMA wire which includes changes of electrical parameters in conjunction to mechanical parameters. Due to the correlation between electrical resistance and mechanical stroke it was possible to implement a resistance-based position control without the necessity of an external positioning sensor. In order to design a linear position controller by common rules the highly complex and nonlinear model was simplified. Controller development yielded a PID algorithm that was implemented on a rapid prototyping system as part of an SMA wire test bench. The models accuracy was verified by various measurements with different wires and multiple loads. Based on that, it was possible to design an actuator which utilizes a flexible socket instead of fixed mountings

1. INTRODUCTION

Due to intense material research in recent years the performance of thermal shape-memory-alloys (SMA) increased considerably, which resulted in numerous new application fields for this kind of intelligent material. The most promising fields of application are determined by the specific actuation characteristics of the material. In addition to thermal activation a very important property is the very high specific workload of actuators made of SMAs. A comparison of the volume specific workload of different actuator types is shown in Figure 1 [7]. From the graph it is obvious that SMA-actuators reach very high work load levels which are nearly five orders of magnitude higher than those obtained for small DC-drives. Research at the Fraunhofer IWU is therefore focused on the development of small SMA-drives. The major benefits of such drives are a significantly reduction in scale, weight, and costs.



(a) specific work load (b) petrol cap locking device

Figure 1: Comparison of different actuator types and application of SMA-wires in switching drives.

Thermal shape memory alloys offer the special ability to "remember" and re-assume their original shape following permanent plastic distortion below a specific critical temperature by means of heating up above this

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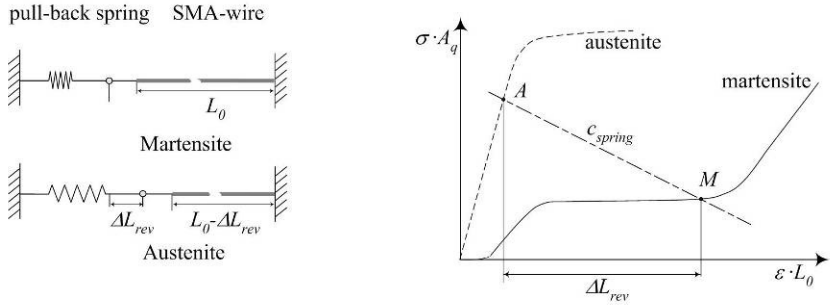
temperature. A reversible austenite-martensite phase transformation is required for the development of the shape memory effect. Analogous to steel the high temperature phase β of the material is also described as austenite and low temperature phase α as martensite. In an ideal situation the austenite β phase is converted into the martensite α phase as a result of shear. Due to diffusion-free rearrangement processes in relation to the atoms this generates a change in the stacking sequence of the crystal lattice levels and therefore a change in the structure of the crystal lattice. Consequently, two different stress-strain-curves exist as shown in Figure 3(b). In the low-temperature phase a small Hook region is followed by a so-called plateau-stress. There the wire can be easily deflected almost without increasing the applied external stress. After setting the stress to zero, a plastic deflection remains to the wire. Heating the wire causes the described phase transformation and results in a completely different stress-strain-behavior. The Hook region is significantly wider; the Young's-modulus is two to three times higher. Applying a high amount of stress causes a so called super-elastic-behavior. During the phase transformation from martensite to austenite (heating) the wire is able to perform mechanical work (see Figure 3 a). The amount of work depends on the mechanical boundary conditions of the wire. In case of a free wire the amount of work would be zero, but the actuator deflection would be maximum. In contrast, blocking the wire causes a very high actuation force but no deflection. The work output is also zero. Using a spring with a defined stiffness as boundary element instead, causes a deflection as well as a reaction force and therefore a usable workload. The amount of that workload depends on the stress-strain-curves of the material and the design of the spring. The mechanical design of such actuators has been described previously and details can be found in [2].



(a) mechanical principle (b) stress-strain behavior

Figure 2: Mechanical arrangement.

The estimated benefits of SMA wire actuators, i.e. reduced mass, scale and costs meet the current demands of several industry sectors. Many of the currently applied drives need to perform a linear stroke of several millimeters with a force level ranging from several Newton up to several 10 Newton. A part of them exclusively operate in switching mode. Figure 1 b shows for instance an SMA drive for locking a petrol cap of a car compared to a DC-drive with gear head and steering rod. The design process of a switching drive is focused on the mechanical function. The thermal design only has to prevent an unwanted activation by environmental heat. Consequently no detailed thermal model is needed.

Beyond switching drives there is an increasing number of position controlled drives in several industry sectors. Realizing these drives by using SMA-actuators necessitate a position control of the wire. To design an adequate controller the limitation to mechanical aspects is not sufficient. In fact the thermal behaviour of the actuator rather has to be focused. Therefore, an overall model to simulate the SMA-wire and above all to design the controller is necessary. In order to promote the industrial application of SMA-actuators, the model should not only be used to simulate the actuator system, it also has to clarify the essential aspects of control design, considering a selective design of a simple control algorithm.

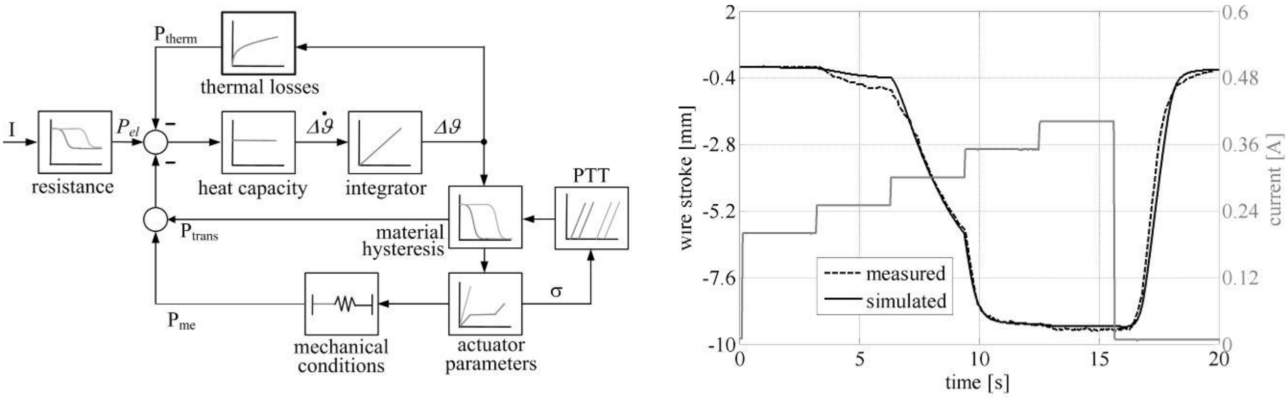
2. Numerical Model of The SMA-Wire-Actuator

There are different approaches to model SMA-actuators. Micro structural approaches are used to describe physical processes, but are not suitable for describing the macroscopic behavior of an actuator [9]. Another way to model SMA-actuators is to use phenomenological models. The problem in using such approaches is not to loose the physical dependencies by using the mathematical approaches. The implemented parameters are derived by mathematical approaches and do not contain physical information about the actuator [1]. In contrast, the modeling approach reported in [8] constrains the mathematical approach to the inner behavior of the material. This yields physically defined model parameters, which are either given in the material specification or can be measured.

To understand the complex activation behavior and to determine different control algorithms, Fraunhofer IWU developed a Matlab®-based simulation tool using the approach given in [8] to emulate the properties of an SMA wire [3]. The tools basic principle is the power balance shown in Eq. 1. The contained terms result of the characteristic material behavior combined with the thermal and mechanical boundary conditions and can be described briefly by:

$$P_{el} = P_{heat} + P_{therm} + P_{me} + P_{trans} \,. \qquad (1)$$

The energy input is represented by a defined electrical current which is applied to the SMA-wire. As a result of the electrical resistance of the wire, thermal energy is induced and an activation power is delivered to the SMA-material. This power meets some negative feedback mechanisms such as thermal convection and thermal radiation as shown in Fig. 3 a.



a) model structure b) model validation during laboratory measurement

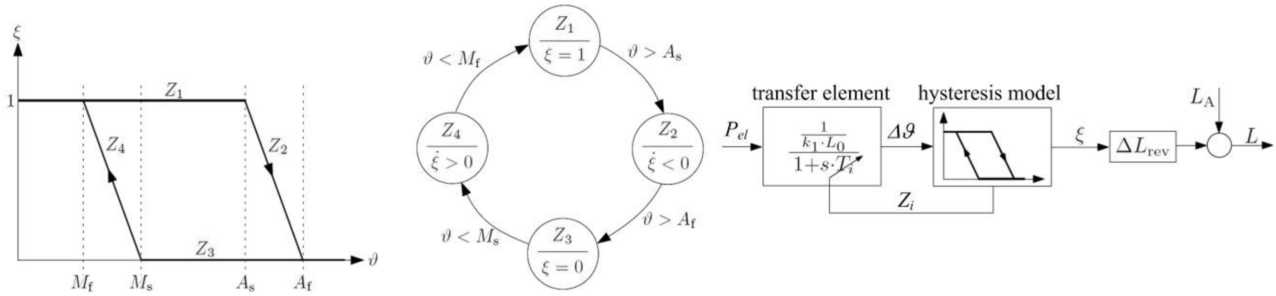
Figure 3: Model of a SMA-wire actuator basing on the power balance.

The residual thermal power P_{heat} applied to the SMA-actuator causes a temperature variation. A specific characteristic of the SMA's behaviour is the discrete occurrence of the phase transformation process, which is modeled by a finite state machine. That enables to change the process depending on rising or falling temperature. During the phase transformation process the wire delivers a mechanical power P_{me}.

The formulation of equations for these power terms lead to a complete description of the dynamic behavior of a SMA-wire. The model can be numerically solved and correlates approximately with the results of the measurement as shown in Fig. 3 b.

3. Model reduction

For an effective control design a linear description of the control plant is essential. Due to the thermal hysteresis a linearization of the model described (see point 2) at a defined work-point is not possible. Hence an other approach using piece-wise straight lines can be developed. The principle idea is shown in Figure 4 a. Transition between the straight lines effects discrete and is triggered by over- or under running a defined temperature. The description of the event-discrete behavior is realized by defining the states and transitions shown in Figure 4 b. State Z_2 and Z_4 represent the material whilst phase transformation that means the material changes its structure and has therefore actuating characteristics. In states Z_1 and Z_3 the material has a complete martensitic or austenitic structure and behaves as passive material.



(a) simplified hysteresis mode (b) state graph (c) simplified transfer behavior

Figure 4: Model reduction.

Combined with a linear approach for the convection heat, neglecting the mechanical power, the model of the SMA-wire actuator can now be described in linear form. Considering the different transfer behavior in the states Z_1/Z_3 and in Z_2/Z_4, two different models based on Eq. (1) have to be created.

To describe the transfer behavior in states, Z_1/Z_3 Eq. (1) can be simplified to:

$$P_{el} = m \cdot c_p \cdot \Delta\dot{\vartheta} + k_1 \cdot L_0 \cdot \Delta\vartheta \,. \qquad (2)$$

Transforming into Laplace-domain, neglecting the initial value and solving for $\Delta\vartheta$ results in the dynamic transfer behavior from an electrical input power to the wire temperature:

$$\Delta\vartheta(s) = \frac{1}{k_1 \cdot L_0} \cdot \frac{1}{1 + s \cdot T} \cdot P_{el}(s) \,. \qquad (3)$$

This behaviour corresponds with the one of a first order lag-element. The response time:

$$T = \frac{m \cdot c_p}{k_1 \cdot L_0} = \frac{\pi \cdot c_p \cdot \rho \cdot d^2}{4 \cdot k_1} \qquad (4)$$

does not depend on the length but on the diameter of the wire like the convection constant k_1.

To calculate the transfer behavior of the actuator in states Z_2 and Z_4 Eq. (2) has to be extended by the enthalpy power which occurs during the phase transformation P_{Trans}. The transformation enthalpy acts as additional heat capacitance, whereby the first order lag-element-behavior is also valid during the phase transformation. In contrast to Eq. (4) the time-constants of the system are different, depending on heating or cooling the wire. They are significantly bigger compared to Eq. (4). That means that the transfer behavior is slower whilst the transformation.

Figure 4 c shows the scheme of the developed linear model. It consists of a first order lag element with a variable time constant and a line based hysteresis element. The hysteresis element defines the state of the actuator in dependency of the temperature. The time constant then is chosen by the actual state of the wire. The model is now suitable for designing a position control loop.

4 CONTROL DESIGN AND IMPLEMENTATION

4.1 THE LENGTH – RESISTANCE CORRELATION

The development of applications with continuous positioning demands always requires a closed loop control of the actuator stroke. These control loops usually necessitate an external position sensor. SMA control loops rather can be designed without an external position sensor, because the material behaviour possesses to get information about the actual stroke only by measuring the resistance [4]. During the phase transformation from martensitic to austenitic lattice and the so involved changes in the structure of the SMA-material, the status of transformation correlates with the electrical resistance. In fact the lattice structure in austenite state is more regular than in martensite state. Therefore the specific electrical resistance of austenite is significantly smaller than the one of martensite. The information of the actual wire stroke can be determined by measuring the electrical resistance during positioning operations. Compared to the implementation of an external position sensor this can be achieved by significantly less effort, because an electrical interface is needed anyway to control the power input of the actuator.

As shown in the references [8], [5], there are different possibilities to model the length-resistance-correlation of SMA-wires. That varies from elementary linear approaches to complex approaches considering the temperature variance of the specific resistance and the changing geometry during the deflection of the wire. According to planned applications an implementation of a microcontroller is necessary. In combination with the requirements regarding the positioning accuracy of flaps using a linear approach seems to be adequate. In [7] a linear interpolation of the specific resistance from martensite ρ_A to austenite ρ_M in the form:

$$R = \left[\xi \cdot \rho_M + (1-\xi)\, \rho_A \right] \cdot \frac{L_0}{A_q} \tag{5}$$

is published. The Elimination of the martensite amount ξ results in a linear correlation of wire length and resistance:

$$L = L_M - \frac{\Delta L_{rev}}{\Delta R_{rev}} \cdot \left(R_M - R \right) \cdot \tag{6}$$

In this equation ΔL_{rev} and ΔR_{rev} are the maximal differences of the wire resistance and the achievable stroke during the phase transformation (see Figure 5).

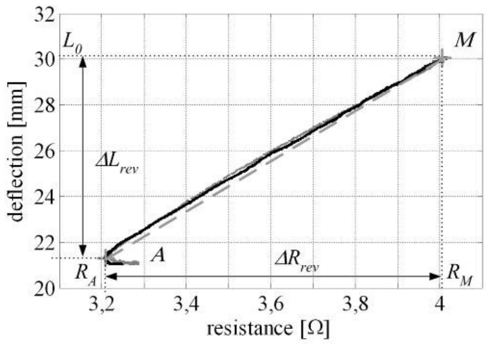


Fig 5: Measured length-resistance-correlation (NiTiCu-wire Memry GmbH).

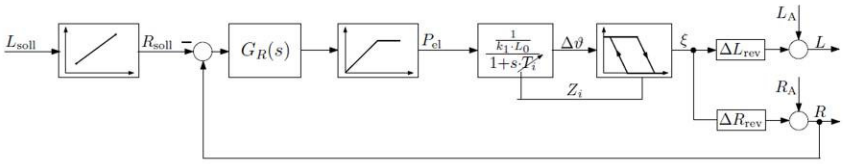
Implementing the correlation to transform a given reference position L_{ref} into a reference resistance R_{ref} as described in the following chapter requires a solution of the reference resistance:

$$R_{ref} = R_M - \frac{\Delta R_{rev}}{\Delta L_{rev}} \cdot L_{ref} \cdot \tag{7}$$

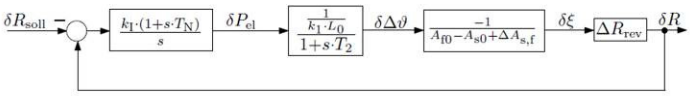
It has to be remarked, that the reference position L_{ref} always represents a contraction of the wire and decreases from the maximum wire length in full martensite state. The required resistance and stroke values can be determined by measurements or calculations regarding the geometrical dimensions and the material parameters of the wire.

4.2 CONTROL DESIGN

The model developed in chapter 2 and 3 includes a hysteresis element, which makes the realization of the position control relatively ambitious. Nevertheless linear control approaches are a suitable choice. This is caused by the simplicity of the algorithms and the possibility to optimize the controller only by adjusting a few parameters. Furthermore such control algorithms are relatively robust concerning possible variations in actuator parameters. Overall linear controllers offer the possibility to realize adequate closed loop controls without being an expert in control design.



(a) feedback



(b) linearized feedback loop (State Z_2)

Figure 6: control of the SMA-wire actuator.

The structure of the control loop is displayed in Figure 6 (a). The plant is represented by the simplified model developed in this paper. The reference value of the control loop is calculated by transforming the desired position L_{ref} with the length-resistance-correlation according to Eq. (7) into a reference resistance value. The control loop in fact is actually a resistance control loop rather than a position control loop. Using this arrangement provides the benefit to change the used length-resistance-correlation without changing the whole control loop. The structure of the control loops considers the negative feedback of the wire resistance. That means an increasing of electrical power P_{el} causes a decreasing of the resistance R. Considering the real resistance-length-correlation, as shown in Figure 5 (a), working near the end of the phase-transformation-region this coherence changes into a positive feedback causing instability of the control loop. To avoid this, suitable sanctions have to be established but they are not focused in this paper. The control loop furthermore consists of the linear controller G_R and a saturation element resulting by the limited performance of the power amplifier and the passive cooling approach.

The hysteresis element and the continuous changes in time constant of the plants avoid the design of one controller for all operation ranges. The controller rather has to be adaptive or an operation range has to be defined. Considering the operation mode of a position control loop, the controller will mostly operate in the actuator states Z_2/Z_4 (during phase transformation). Designing a non-adaptive controller adjusted to the time constant T_2 seems to be adequate because the difference between T_2 and T_4 is relatively small. Choosing an operating point enables to simplify the whole control structure (see Figure 6 (a)) to a completely linear control loop as shown in Fig. 6 (b). The plant only consists of a simple first order lag element and can be controlled by a simple PI-controller that is written in Laplace-domain as:

$$G_C(s) = k_c \cdot \frac{(T_c s + 1)}{s}. \tag{8}$$

Choosing the controller time constant T_c in a way, to compensate the plants time constant T_2 results for the closed loop in a first order lag-behavior without overshoot as described by:

$$\frac{R(s)}{R_{ref}(s)} = \frac{1}{k_c \cdot k_p \cdot s + 1}. \tag{9}$$

The time constant of the closed loop is given by:

$$T_{CL} = k_c \cdot k_p = k_c \cdot \frac{\Delta R_{rev}}{A_{f,start} - A_{s,start} + \Delta A_{s,f}} \cdot \frac{1}{k_1 \cdot L_0} \tag{10}$$

and can be adjusted in a wide range by changing k_c. Whereas the theoretical minimum of the time constant T_{CL} is unlimited in the practical realization the value is limited by the output power of the amplifier.

4.3 ACTUATOR SETUP AND RESULTS

The developed actuator module is an independent, easy to integrate component that is especially suitable for applications with high positioning demands and limited cross sections. As shown in Fig. 7 the actuator concept is based on a shape memory wire that is implemented in a flexible Bowden cable casing. The fixed mounting of the casing allows using the stroke of the activated wire at the effector.

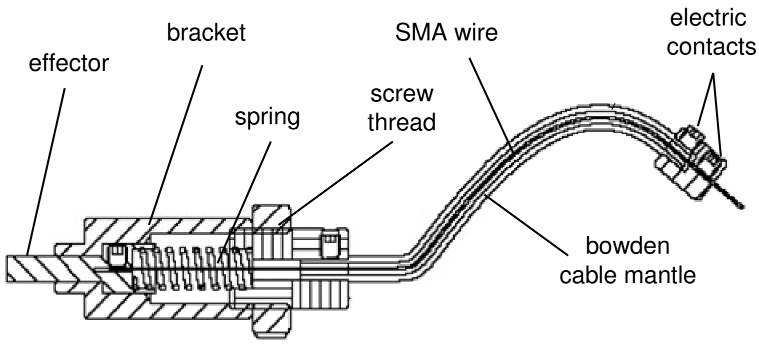


Fig 7: Bowden cable actuator

An integrated spring with a defined stiffness as boundary element guarantees resetting to the initial state and realizes a defined end position. The specific pre stress that is needed for SMA's and the so resulting stroke can be set by a thread in the bracket. Furthermore it is possible to set the actuator properties by the length of the Bowden cable and the SMA wire. The electrical power is applied by two insulated contacts at the end of the actuator. The bowden cable mantle operates as low resistance return contactor.

The control algorithm described in point 4.2, was implemented at a dSpace®-Rapid prototyping hardware. The controller parameters were directly determined using the simplified plant model, given in Eq. (1). No additional adjustments during implementation were necessary. The performance of the control loop was investigated by laboratory measurements and is shown in Fig. 8.

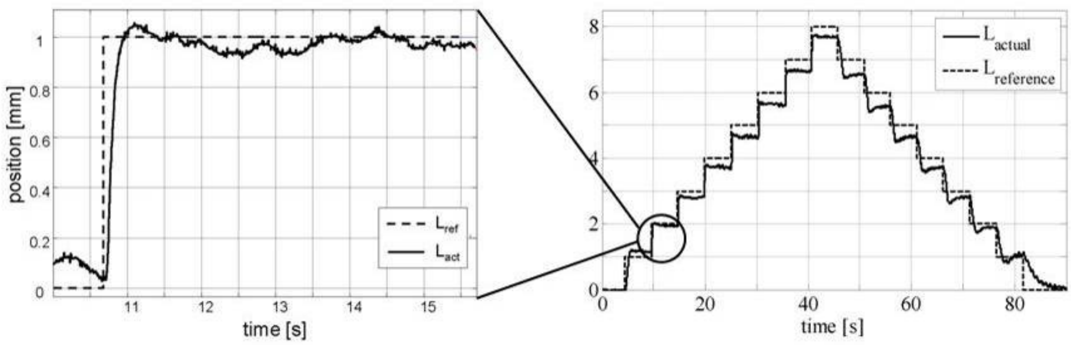


Fig. 8: Step response of the resistance controlled actuator

The maximal deviation occurs at the maximal actuator stroke of 8 mm and is about 5%. This is caused by the linear approximation of the stroke-resistance-correlation. Regarding Fig 5 it is obvious that near R_A the deviation of the approximation is maximum.

5 Summary and Outlook

Shape-memory-alloys (SMA) are easy to integrate into mechanical structures and capable of handling high specific workloads. Therefore, SMAs possess an outstanding potential to serve as positioning devices in various applications. In modern cars for example a multiplicity of electrical drives are used. The applications reach from locking devices over adjusting systems to flap drives. In the air conditioning systems for example exclusively electrical DC-drives are used. Due to its high specific workload, Shape-Memory-Alloys are a promising alternative. The estimated benefit is the possibility to design significantly smaller and cheaper drives in comparison to conventional DC-drives. However, due to the non-linear material behaviour it is often difficult to develop suitable controllers for SMA positioning applications. We presented here the multi-domain modelling of an electrically heated SMA wire which includes changes of electrical parameters in conjunction to mechanical parameters. Due to the correlation between electrical resistance and mechanical stroke it was possible to implement a resistance-based position control without the necessity of an external position sensor. In order to design a linear position controller by common rules the highly complex and nonlinear model was simplified to an easily manageable model.

Controller development yielded a PI-algorithm that was implemented on a micro-controller based system as part of an actuator. The performance of the controller was validated during laboratory measurements. Compared to electromechanical DC-drives the system fulfills all requirements, with little constraints in position accuracy and power consumption. The main benefit of the SMA-drive is the significant reduction of complexity resulting in a perspicuous reduction in production costs.

Further work will focus on increasing the accuracy of the position control by applying more exact approximations of the length-resistance-correlation. Other points to clarify regard effects of the controlled operation mode. First of all there is the permanent power consumption caused by the continuous heating of the material. One possible solution is the usage of mechanical detents to allow switching off the heating current. Another one is using a second SMA-wire in an antagonistic operation mode. The second problem to be solved is related to the durability of the SMA-actuator. Whereas durability aspects are known for actuators used in cyclic mode for position controlled actuators this effect is rather unexplored. The major aspect to clarify is the influence of small but often occurring fluctuations in the amount of martensite, caused by small changes in the reference position and fluctuations of environmental parameters.

Beyond that the achieved results are an essential part of the continuous development of SMA applications. The successful development of SMA - based switching devices as step one and the presented SMA-actuator model and control as step two, establish the basis for the primary objective, the development of energy self-sufficient systems. The acquired knowledge will be used to develop independent components for industrial engineering. This includes for instance thermo stable machine beds to increase precision as well as adaptive ball screw drives or spindle ball bearings to decrease friction and abrasion.

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