Design of a Controllable Shape-Memory-Actuator with Mechanical Lock Function

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ABSTRACT

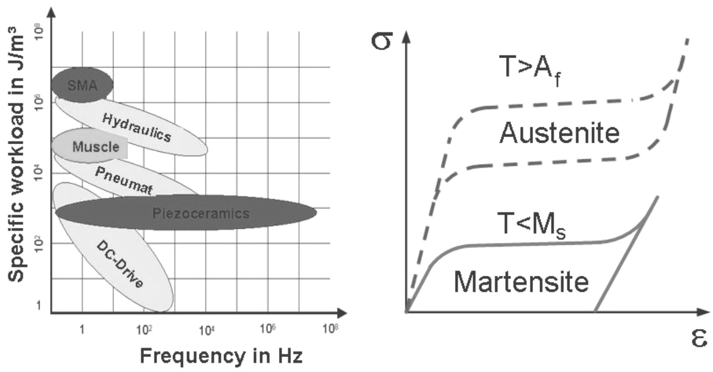
Machine tools for small work pieces are characterized by an extensive disproportion between workspace and cross section. This is mainly caused by limitations in the miniaturization of drives and guidance elements. Due to their high specific workloads and relatively small spatial requirements, Shape-Memory-Alloys (SMA) possess an outstanding potential to serve as miniaturized positioning devices in small machines. However, a disadvantage of known actuator configurations, such as SMA wire working against a mechanical spring, is that energy is steadily consumed to hold defined positions. In this paper we present a novel SMA actuator design, which, due to an antagonistic arrangement of two SMA elements does only require a minimum amount of energy whilst holding position. The SMA actuators were designed regarding material, geometrical parameters, applied load, and control aspects. Furthermore, closed loop control concepts for positioning applications are implemented. These not only cover approaches using sensors, but also sensor-less concepts which utilize the distinctive length – resistance - correlation of SMAs for position controlling. Furthermore, an actuator demonstrator has been used to demonstrate the designs capabilities to serve as miniaturized positioning device in small machines. In addition the novel design concept of the SMA actuator will be compared with commonly used approaches.

Keywords: Shape-Memory-Alloy, position control, actuator, constant load, spring load, antagonistic wire, sensor less control

1. INTRODUCTION

Modern high precision machine tools for small work pieces are usually downscaled equivalents of macro scale machine tools. The dimensions of applied machine components like drives, guidance elements and supports do not significantly differ. Hence the cross section of such machines is related to their big counterparts. Due to the rather small workspace of these machines they are characterized by an extensive disproportion between workspace and cross section. The dimension of the machine commonly exceeds the dimensions of the work piece by orders [1]. This effect is manly caused by two reasons. Firstly, the miniaturisation of drives is limited because their physical principle necessitates minimum sizes. Secondly, guidance elements need a certain dimension to realize the expected stiffness. Active materials like SMA offer an outstanding potential to overcome this disproportion.

Due to intense material research in recent years the performance of thermal SMAs 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 extraordinary high specific workload of actuators made from SMA. A comparison of the volume specific workload of different actuator types is shown in Figure 1 (a). From the graph it is obvious that SMA-actuators reach very high work load levels which are nearly three orders higher in magnitude than those obtained for small DC-drives. Furthermore Figure 1 (a) shows, that DC-drives and pneumatic or hydraulic actuators are subjected to scaling effects. Only small actuators with low specific workloads can realize high frequencies. In contrast only big actuators with small working frequencies feature high specific workloads. SMAs are rather not subjected to these restrictions. Due to their high specific workloads, relatively small spatial requirements and no scaling limitations SMAs possess an outstanding potential to serve as miniaturized positioning devices in small machines [2].



(a) Specific work load (b) Stress-Strain-Behavior of SMAs

Figure 1: Comparison of different actuator types and availability of SMA-material

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 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 1(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 1 (b)). 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 constant load or 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 constant load or spring. The mechanical design of such actuators has been described previously and details can be found in [3].

There are several known systems basing on these approaches. They range from switching applications as described in [4], [5], [6], up to position controlled systems as described in [7],[8]. These systems whether controlled or not require a continuous power input to hold defined positions. Another approach as described in [9] uses two one-way SMA-wires in an antagonistic arrangement to overcome this problem. However, the described system is not closed loop controlled.

In this paper we present the development of a closed loop controlled SMA actuator with two wires in antagonistic arrangement. The actuator is compared with similar actuators designed by the other principles (constant load, spring load).

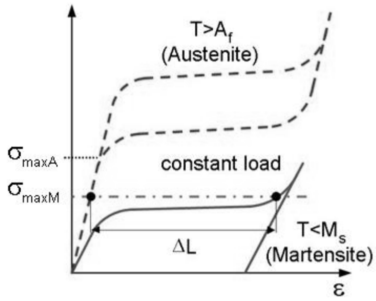
2. ACTUATOR PRINCIPLES

Pre-stretched one-way SMA wires contract by heating above a certain austenite start temperature. However, without an applied load these wires do not deform to their origin position upon cooling. Systems using one-way SMA wires therefore have to be used in combination with a force creating (pull back) component as for instance an applied constant load (mass), a spring or an antagonistic arrangement of two SMA wires.

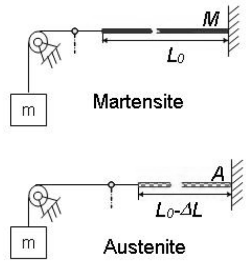
2.1 Constant Load

The first approach to realize a pull-back force is applying a constant load (mass) on it. Figure 2 (b) shows the mechanical principle. The cold actuator in martensite state is strained by the load until it reaches a certain stress level (see Figure 2

(a) solid line). Heating the wire causes the described phase transformation and results in a contraction of the wire by ΔL until it reaches the austenite stress-strain-curve.



(a) Stress-Strain-Behavior



(b) mechanical principle

Figure 2: SMA wire working against constant Load

Cooling the wire results in a reverse phase transformation and the load pulls the wire back as far as the complete martensite state is reached. The amount of work that is performed to move the actuator is defined as

$$W_{PB} = m \cdot g \cdot \Delta L = \sigma_{\max M} \cdot \frac{\pi \cdot d^2}{4} \cdot \Delta L \,. \tag{1}$$

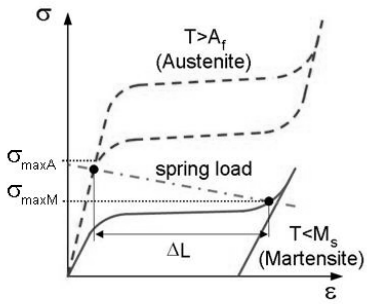
The value of usable actuator work is

$$W_A = (\sigma_{\max A} - \sigma_{\max M}) \frac{\pi \cdot d^2}{4} \cdot \Delta L \,, \tag{2}$$

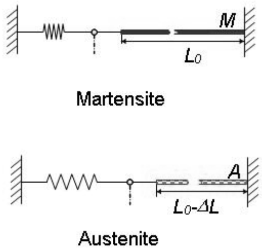
where $\sigma_{\max A/M}$ is the maximum applicable stress in austenite/martensite state and d represents the diameter of the wire.

2.2 Spring Load

Using a pre tensioned spring with a defined stiffness (Figure 3(b)) as pull-back element instead, also causes a deflection as well as a reaction force. However, the applied stress on the wire increases due to the rising force characteristics of the spring.



(a) Stress-Strain-Behavior



(b) mechanical principle

Figure 3: SMA wire working against pre tensioned Spring Load

The sum of work that is performed to move the actuator is.

$$W_{PB} = \sigma_{\max M} \cdot \frac{\pi \cdot d^2}{4} \cdot \Delta L + \frac{1}{2} c \cdot \Delta L^2 \,. \tag{3}$$

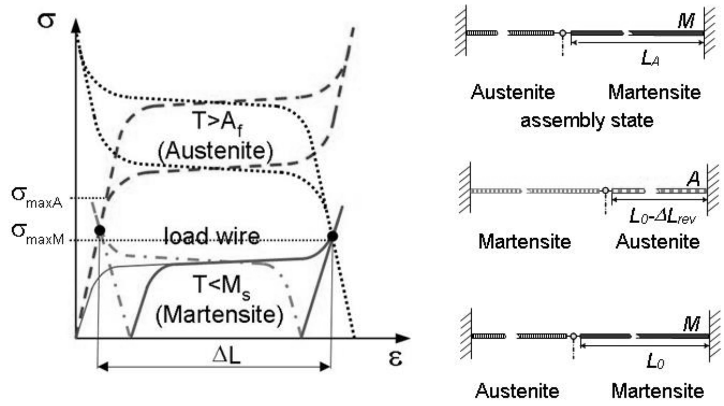
The amount of usable actuator work is

$$W_A = (\sigma_{\max A} - \sigma_{\max M}) \frac{\pi \cdot d^2}{4} \cdot \Delta L - \frac{1}{2} \cdot c \cdot \Delta L^2 . \quad (4)$$

It is easily visible that the amount of usable work decreases (depending on c) compared to the constantly loaded wire. Furthermore the usable force of the actuator decreases with an increasing deflection of the spring. This behavior is disadvantageous for the application as positioning drive for machines because there it is necessary to offer a constant amount of usable force over the whole range of the actuator.

2.3 Antagonistic Wire

Compared to the other actuator principles the antagonistic arrangement has the advantage that only the necessary pre tension is applied to the SMA wire. Figure 4 shows that the pre-tension on the wire is significantly lower (dash-dot-line of the load wire).



(a) Stress-Strain-Behavior (b) mechanical principle

Figure 4: SMA wire working against antagonistic SMA wire

The amount of work that is performed to move the actuator is defined by

$$W_{PB} = \int_{\varepsilon_0}^{\varepsilon_{\Delta L}} \sigma(\varepsilon) d\varepsilon . \quad (5)$$

The amount of usable actuator work is defined by

$$W_A = \sigma_{\max A} \cdot \frac{\pi \cdot d^2}{4} \cdot \Delta L - \int_{\varepsilon_0}^{\varepsilon_{\Delta L}} \sigma(\varepsilon) d\varepsilon . \quad (6)$$

As visible in Figure 4 the usable work of the actuator is higher compared to the other actuator principles because only a minimum of energy is needed for moving the actuator. As described in [9] switching off the energy supply is not possible. In that case the actuator would release his tension and though move by the amount of his elastic deformation (dash-dot-line) and cause a non tolerable positioning error.

Another important aspect the actuator principles have to be investigated for is the dynamics. It has to be remarked, that the discussion in this paper only corresponds with heating the wire. The cooling procedure rather necessitates other aspects to be considered. The dynamic behavior of an SMA actuator is defined by the phase transition temperatures. As described in [10] there is a characteristic transfer time constant that defines the transfer from martensite to austenite. This time constant decreases with an increasing difference between austenite start A_s and - finish temperature A_f. As shown in Figure 5 this difference depends on the actuator principle (constant/decreasing/increasing load). Hence the actuator principle wire against spring and the antagonistic arrangement should possess a faster transfer behavior compared to the constant load arrangement.

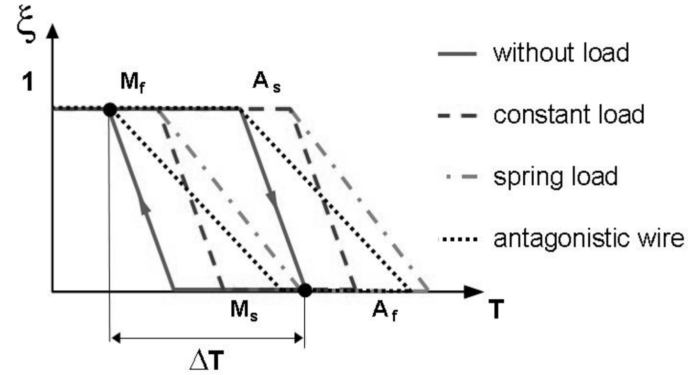


Figure 5: Phase-Transition-Temperatures depending on the mechanical boundary conditions

Beyond the influences of the boundary conditions to the time constant there are other aspects that have to be considered. First of all there is a certain temperature interval (from martensite finish M_f to austenite finish A_f) that has to be passed for a complete phase transformation. As described in [11] the mechanical boundary conditions affect this temperature interval. It increases with an increasing load applied to the wire. The second aspect is related to the ambient temperature. Increasing phase-transformation temperatures result in a rising temperature difference between ambient and phase-transformation temperatures. Due to the limited actuating variable both influences will affect the dynamic behavior of the system. Whichever effect has a bigger impact will be discussed in chapter 4.5.

3. CONTROL CONCEPT

The material behavior of SMAs is strongly nonlinear, which makes the realization of the position control relatively ambitious. Nevertheless linear control approaches as described in [10] 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 profound knowledge in control design.

3.1 Control via External Position Sensor

Controlled drives for positioning applications always require a closed loop control of the actual position. Due to the high precision demands of the actuator the control loop necessitates an accurate external position sensor. This can be achieved by the applied laser triangulation sensor. Under certain circumstances as described in [8] the plant of an SMA wire can be described by a simple first order lag element that can be controlled by a simple PI-controller. However, the integral part of the controller is always set as a compromise between heating and cooling and would be different for the three actuator principles. Due to the necessarily comparability of the actuator principles this work only focuses on the application of simple proportional-controllers.

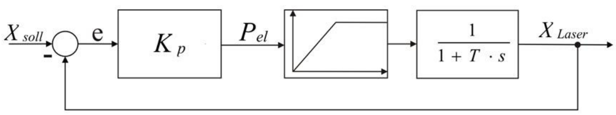


Figure 6: Simplified Control loop of an SMA wire

Figure 6 shows the simplified control loop of a single SMA wire that consists of a p-controller, a power limitation and the plant as a first order lag element.

3.2 Sensorless Control

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 behavior possesses to get information about the actual stroke only by measuring the resistance [7]. During the phase transformation from martensite 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 [6], [10], 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 the planned application an implementation on a rapid prototyping system is necessary. In combination with the requirements regarding the positioning accuracy of the intended positioning devices using a linear approach seem to be adequate. In [4] a linear interpolation of the specific resistance from martensite ρ_A to austenite ρ_M in the form:

$$R = \left[\xi \cdot \rho_M + (1-\xi)\,\rho_A\right] \cdot \frac{L_0}{A_q} \tag{7}$$

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

$$L = L_M - \frac{\Delta L_{rev}}{\Delta R_{rev}} \cdot \left(R_M - R\right) \cdot \tag{8}$$

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 7).

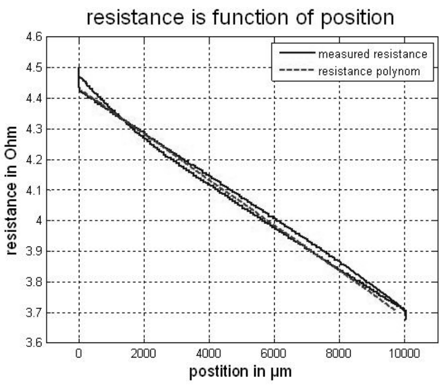


Figure 7: Measured length-resistance-correlation (X2-wire Memry GmbH, l = 400mm, d = 0.38mm).

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:

$$R_{ref} = R_M - \frac{\Delta R_{rev}}{\Delta L_{rev}} \cdot L_{ref} \cdot \tag{9}$$

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.

The control structure equals the control loop in Figure 6 but it rather has an additional resistance calculation in the feedback loop.

3.3 Control Concept for the Antagonistic Arrangement

The existence of two SMA actuators in antagonistic arrangement necessitates an enlargement of the plant by an additional first order lag element that represents the second SMA wire. The wires are coupled at their mechanical output (see Figure 8). As described in [10] the phase transition temperatures of SMAs increase with an increasing tension. This correlation possesses to raise these temperatures in the first wire by heating the second [11]. Due to the increasing difference between ambient and phase transformation temperatures in the first wire the transformation from austenite to martensite will occur faster. To benefit from this effect the control concept bases on splitting the control value. As shown in Figure 8 the first actuator only acts in case of positive control values and the second actuator only acts for negative values.

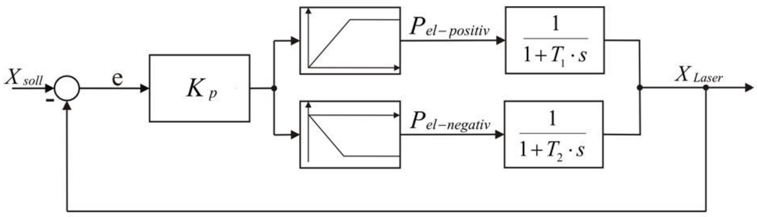


Figure 8: Control concept for the antagonistic arrangement

Due to the coupling between the SMA wires it has to be considered that only one wire is heated at a certain time. This is realized by the limitation of the mechanical tension between the wires. If the tension exceeds a defined constant the control value is set to zero either until the tension decreases or the control values sign changes.

4. EXPERIMENTAL RESULTS

4.1 Experimental Setup

The main demand for the experimental setup is to investigate different actuator principles under the same conditions. Hence a modular test bench as shown in Figure 9 is designed to fulfil these requirements. This configuration offers to implement all imaginable load conditions on an SMA wire. The load defining elements can be connected to the moving mass on a slide way. The SMA wire is applied to the other side of the mass. An integrated force sensor is implemented to detect the tension in the wire. The position measurement is realized by a laser triangulation sensor.

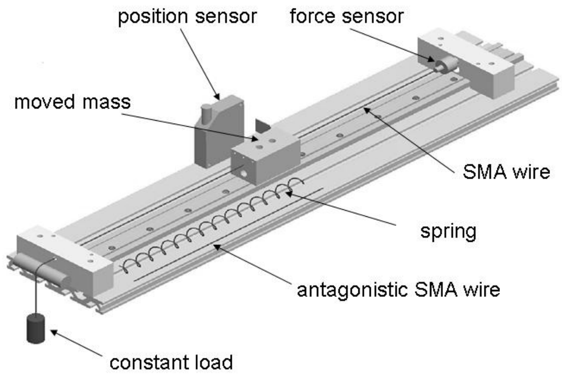


Figure 9: Experimental setup - test bench

SMA wires of small diameters can be heated by electrical power that is applied by two insulated contacts at the ends of the wire. The power supply is realized by controlled current sources. The control algorithms described in chapter 3 can be implemented at a dSpace®- rapid prototyping hardware that is connected to the current sources and the sensors. The proportional-controller gain is experimentally determined using test functions. The performance of the control loop is investigated by laboratory measurements and is explained in the following chapters.

The applied SMA is a NiTiCu-alloy (X2 Memry GmbH) that features a relatively small hysteresis and an almost linear length-resistance correlation. The wire is designed to realize a usable force of at least 10N as described in [3]. It results in a wire diameter of 0.38 mm. An applied pre tension of 2.5% necessitates a length of 40cm to offer a positioning range of 10mm. The tension is limited to 200 MPa.

4.2 Constant Load

The first actuator principle to be investigated is the constant load. A stress-strain measurement of the applied wire results in a tension of 100 MPa at 2.5% strain. So the load mass is calculated to be 1 kg. The length-resistance-correlation is determined by measuring current, voltage and position. It is implemented in the control algorithm as linear function.

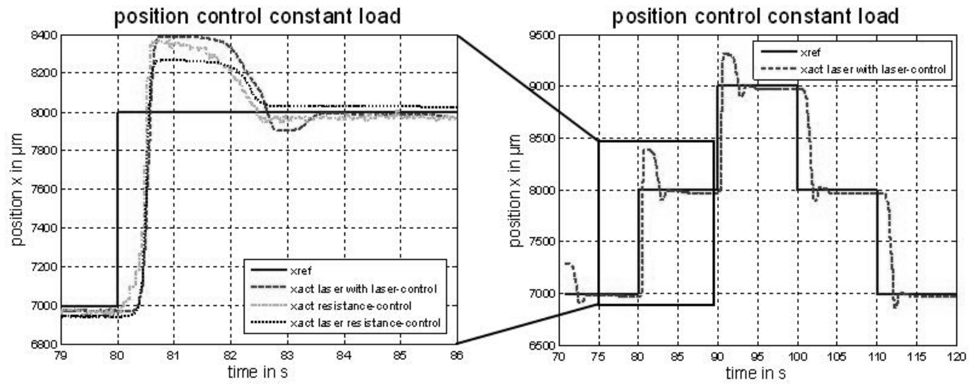


Figure 10: Measured step response for an SMA wire working against constant load

Figure 10 shows the measured step response over the middle positioning range with one step zoomed. The dash-line represents the system in position control mode (laser). The sensor less control (dotted line) shows almost the same results. The reason for the overshoot is related to the proportional controller. The application of a PI-controller with a limited gain would solve this problem but would also prohibit the comparability as described in 3.1.

4.3 Spring Load

After investigating the constant load configuration a load spring is installed instead. The spring is designed to have a minimum stiffness but can also realize the necessary pre-tension of 100MPa. The design process yields a spring with a stiffness of 0.2N/mm which is pre strained by 50 mm.

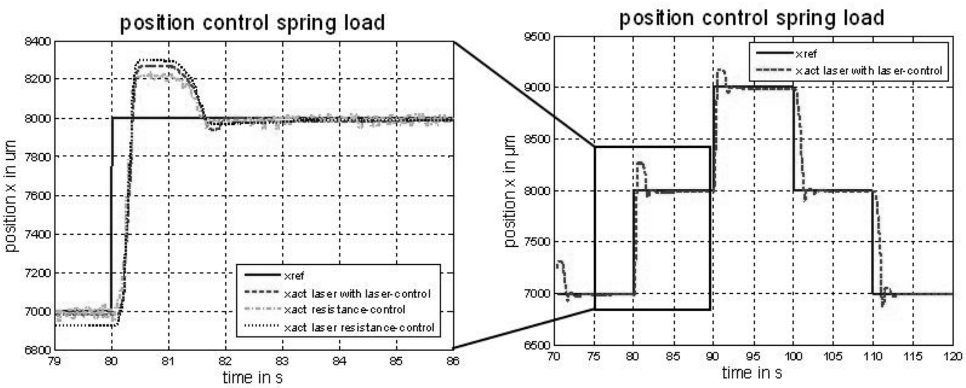


Figure 11: Measured step response for an SMA wire working against pre tensioned spring load

As visible in Figure 11 the rise time and the overshoot is smaller compared to the constantly loaded wire. Furthermore the step function shows a shorter time for reaching steady state. There is no significant difference between laser- and resistance control.

4.4 Antagonistic Wire

The last actuator principle to be investigated is the antagonistic wire. The SMA wire can be installed without any pre tension if the other wire is already strained.

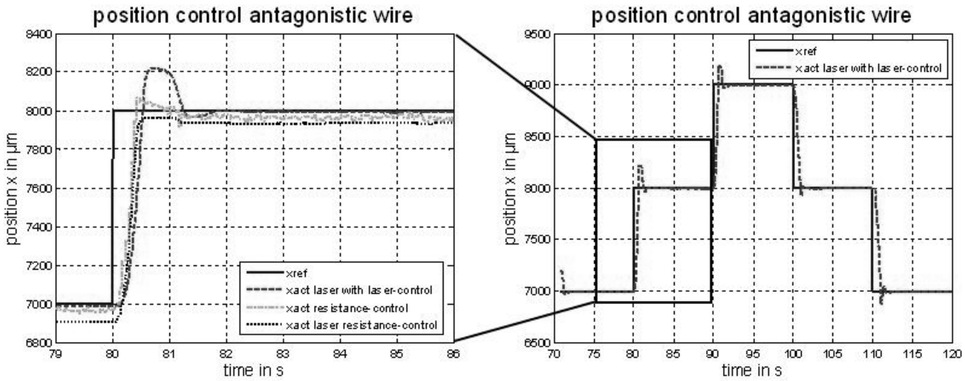
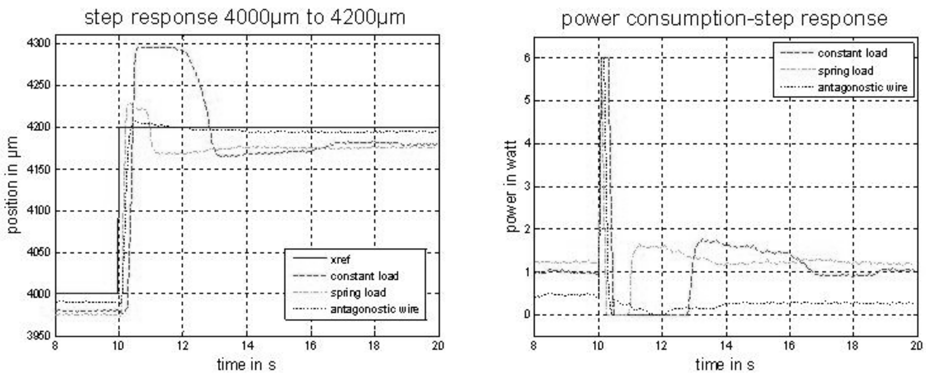


Figure 12: Measured step response for an SMA wire working against pre tensioned spring load

Figure 12 shows the step response of this configuration. The rise time is almost the same as in the other configurations but the overshoot respectively the time for reaching steady state is rather smaller. This effect is related to the control concept of the antagonistic arrangement. Within the first half second of the operation the controller output is positive and so the first wire is heated. When the wire reaches its reference value the controller output gets negative and so the opposite wire is heated. The arising tension enhances the cooling procedure of the first wire until it reaches the reference value and the controller output converges to zero.

4.5 Comparison of the Results

After investigating the different actuator principles they have to be compared considering several aspects. The application of SMA actuators as drives in small machines necessitates high dynamics as well as a high positioning accuracy. Figure 13 (a) shows the step responses of the different actuator principles in laser control mode. It is obvious that the spring loaded SMA wire and the antagonistic arrangement possess a much better positioning behaviour compared to the constantly loaded wire. Besides the shorter rise time they also show a significantly lower overshoot. This effect clarifies the influence of a decreasing time constant with an increasing difference between austenite start A_s and - finish temperature A_f as discussed in 2.3. The other discussed facets of the temperature interval (from martensite finish M_f to austenite finish A_f) that has to be passed and the difference to the ambient temperature show no measurable impact.



(a) position step response (b) power consumtion

Figure 13: Comparison of the actuator principles

Another aspect that has not been regarded yet is the energy consumption. Figure 13 (b) shows the power consumption of the actuator principles during the positioning operation shown in Figure 13 (a). Considering the whole time span of the step response the antagonistic arrangement shows a remarkable low usage of electrical energy. The other actuator principles rather steadily consume at least 1 Watt. This effect corresponds with the applied load. Figure 14 shows the applied tension over the strain for the different principles.

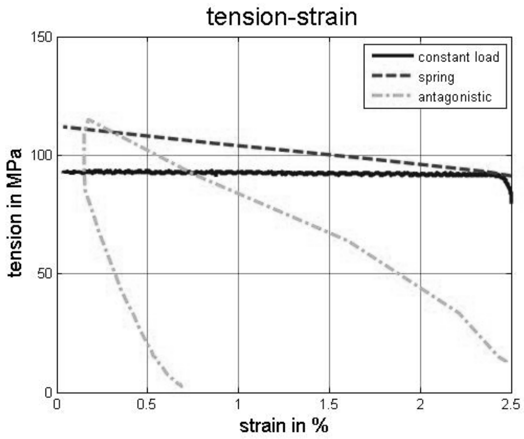


Figure 14: Measured Stress-Strain-Behavior depending on the mechanical boundary conditions

This correlation corresponds with the energy consumption. The spring and constantly loaded wire steadily have to hold a certain pre tension of at least 90 MPa over the whole positioning range. The antagonistic arrangement rather has to apply a minimum tension to keep the load wire stretched. Due to a decreasing tension with an increasing strain the antagonistic arrangement especially consumes less energy at low positions (high strain).

To evaluate the actuator principles considering every aspect Table 1 shows them in total.

Table 1: Comparison of the actuator principles

Attribute	**Constant Load**	**Spring Load**	**Antagonistic Wire**
positioning accuracy (laser control)	25µm	25µm	10µm
Rise time	400ms	200ms	350ms
energy consumption at 1.5% strain	1 watt	1.1 watt	0.5 watt
Maximum applicable Load at 1.5% strain	12N	10N	14N
cross section	medium	Low	high
applicable force within workspace	constant	decreasing	decreasing
practicability	difficult	very easy	easy

A constantly loaded SMA wire seems to be the worst principle to realize a drive for small machines. Besides bad dynamics and comparatively high energy consumption this concept is above all characterized by problems in the practical application. Drives for small machines have to be as compact as possible; the installation of a dead weight would cause several constructive problems. Installing a spring is rather the easiest way to realize the necessary pre tension. However, the high energy consumption and the decreasing applicable force along the positioning range are not acceptable disadvantages for the application as machine drives. The antagonistic arrangement is the only actuator principle that fulfils almost all requirements for drives. The only disadvantage is the non avoidable bigger cross section. However this problem can be solved by a winding configuration of the wires. Especially the low energy consumption qualifies this actuator principle to be used in small machine drives.

5. SUMMARY AND OUTLOOK

Shape-memory-alloys (SMA) are easy to integrate into mechanical structures and capable of handling high specific workloads. Therefore, they possess an outstanding potential to serve as drives in small machines. The estimated benefit is the possibility to design significantly smaller and cheaper drives compared to conventional electrical drives. However, a disadvantage of known actuator configurations, such as an SMA wire working against a mechanical spring, is that energy is steadily consumed to hold defined positions. In this paper we presented a novel SMA actuator design, which, due to an antagonistic arrangement of two SMA elements does only require minimum energy whilst holding position. To show the potential of the new actuator design, three different SMA actuators were designed regarding material, geometrical parameters, applied load, and control aspects. Furthermore, closed loop control concepts for positioning applications were implemented. These did not only cover approaches using sensors, but also sensor-less concepts which utilize the distinctive length – resistance - correlation of SMAs for position controlling. Furthermore, an actuator test bench was used to investigate the three actuator principles. These principles have been compared considering positioning accuracy, dynamics and energy consumption. The development showed the advantages of a controlled SMA actuator in antagonistic arrangement that only consumes a minimum amount of energy to hold defined positions.

Further work will focus on increasing the accuracy of the resistance based position control by implementing the length-resistance-correlation not only as a linear function but rather as a polynomial of higher order. Other points to clarify regard the reliability of the SMA wires. First of all there is the problem of an arising two-way-effect with an increasing number of cycles. This effect currently prohibits to completely switching of the energy supply at certain positions. 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.

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