Development of a shape memory based drive and control concept for a hand prosthesis

André Bucht, Christian Rotsch, Kenny Pagel, Jakob Jung, Holger Kunze
Fraunhofer Institute for Machine Tools and Forming Technology, Nöthnitzer Str. 44, 01187 Dresden, Germany

Abstract:
Shape-memory-alloys (SMA) are easy to integrate into mechanical structures and capable of handling high specific workloads. Therefore, SMA's possess an outstanding potential to serve as positioning devices in artificial limbs. In this article the development process of shape-memory actuated hand prosthesis is presented. SMA actuators are used in a feedback-control-loop to control the displacements of the finger-tips. To design the controller a simple model is derived from the energy flows in the actuator. Instead of using an external position sensor the controller is driven by the measured resistance of the shape memory wire. The controller is implemented on a rapid-prototyping-system and the functionality of the hand prosthesis is validated by gripping a defined cylindrical body in two different ways.
Keywords: shape-memory-actuator, control, self-sensing

Introduction

The demands on hand prosthesis are strongly varying by the mechanical design, applied materials and the drive and control concept depending on the focussed application range. The operation purposes range from simply cosmetic prosthesis over myoelectric external-force prosthesis up to prosthesis systems which are controllable by using a direct nerve connection [1].
Considering several drive concepts lead to a detailed characterisation of different hand prosthesis. Actually used drive concepts, according to [2] are i. a.:

- Electric drives (e.g. „Myohand", Otto Bock Health Care)
- Fluidic actuators (e.g. „Fluidhand", Forschungszentrum Karlsruhe GmbH)
- Linkages, driven by electric drives. („Modular Prosthetic Hand – NTU, Hand III", National Taiwan University)
- Combination of different drive concepts.

The kinematic principle of the human hand is quite complex. According to the literature, from 22 to 26 degrees of freedom are necessary to create a complete kinematic model of a human hand. Starting with a simple kinematic approach to realize prosthesis with many degrees of freedom, the complexity of mechanical design is increasing as well as the size and the weight of the prosthesis. In most cases a position controlled drive including a sensor is necessary to control every degree of freedom. The application of electric drives to realize those many degrees of freedom creates serious challenges in the mechanical design of the prosthesis. In fact size and weight of the prosthesis will reach a level which is not tolerable for the user.

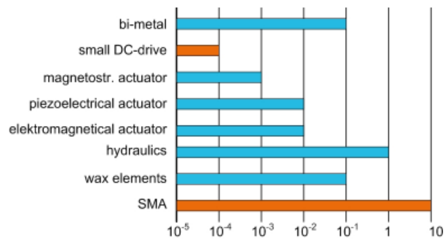

Fig 1: *Workloads of different actuation techniques.*

A suitable approach to overcome this problem is to use shape memory alloy actuators. SMA wires react with a contraction if they are heated above a certain temperature. The heating is accomplished by an electrical current floating through the wire. The technique is superior to adjust the output power accurately. The wires are commonly Nickel-Titanium-alloys what makes them biocompatible. The operation principle, actuation by contraction of a wire, is very similar to the operation principle of human muscles. Compared to human muscles the achievable strain is smaller but the reaction force is higher. A special benefit is the extraordinary specific workload which is even higher then the one of hydraulic actuators.
Besides these benefits there are some challenges in using SMA-wire actuators, especially concerning the mechanical design and the control design. To examine that, Fraunhofer IWU designed a model of a human hand actuated by position controlled SMA-wires.

Mechanical Design

To investigate the applicability of shape memory wires as actuators for prosthesis it is not necessary to develop a model which covers all degrees of freedom of a real human hand. The benefits and the limitations of SMA-wires can rather be demonstrated by using a simplified model. The objective is to realize controlled motions of every single finger and two different kinds to grasp objects:

- between thumb and forefinger (see Fig 5 left) and
- between the middle/ring finger and the metacarpal (see Fig 5 right).

To implement these functions it is sufficient to design a model consisting of three fingers and a thumb, mounted on a common base symbolising the metacarpal (see Fig 2).

Every finger has two rotational joints symbolising the fingers metacarpophalangeal joint and the intermetacarpal joint. The distal interphalangeal joints are not essential to realize grasping functions, they are omitted. In summary the model consists of four fingers with two degrees of freedom.

In robot grippers the electromechanical drives are often directly mounted within the joint. In contrast the shape memory wire actuators of the described hand prosthesis are mounted in the forearm. This requires a transmission of the generated displacement into the fingers. It is realized by using thin flexible steel wires free conducted in the forearm and conducted in a flexible tube made of Teflon while crossing the metacarpal. The end of the wire is fixed on a pulley with a constant radius r. The contraction of the actuator wire pulls the steel wire and causes in a rotational movement of the joint. There are two possible ways to actuate the joints:

- using two SMA-wires to get two independent joints
- using only a single SMA-wire and implement a kinematic coupling of the joints

Because Human finger joints are coupled systems and for simplification reasons the one wire concept was chosen. The hand model therefore consists of four independent wire actuators.

The kinematic principle of a finger is shown in Fig 3. Two passive filaments (1 and 2) are connected to the joints and realise the kinematic couplings. Two other filaments (3 and 4), connected to the “proximal phalanges”, are responsible to actuate the finger.

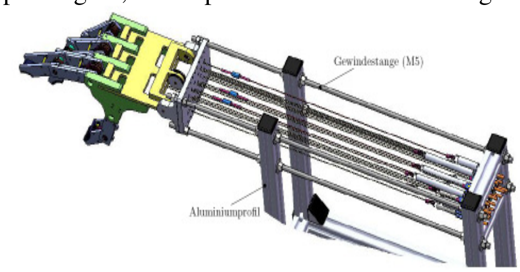

Fig 2: *Realised hand model.*

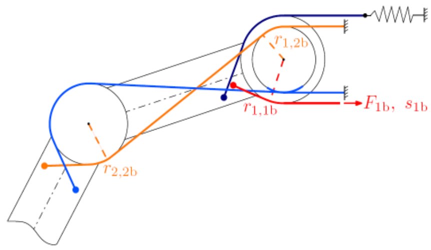

Fig 3: *Kinematic principle of a finger.*

Filament 3 is aligned to a passive pre-stressed spring delivering a pull-back force. The SMA-wire mounted in the forearm is connected to the filament 4.

Considering a cold SMA wire (inactive, deflected) the force generated by the pull-back spring creates a clockwise rotational movement of joint 1 and stretches the finger. So the hand remains opened whilst the SMA-wires are inactive. If the SMA-wire is heated it contracts and rotates joint 1 counter-clockwise. The finger is bending, the hand is closing and the pull-back spring is being deflected. Cooling down the wires result in a decreasing stiffness of the wire and the pull-back spring deflects the wire to its starting length. The description of this kinematic system is not presented in this paper. Further information about that can be found in [3].

The design of the drive chain that considers the wire length l_0 and diameter d and the stiffness of the spring k is also described in [3]. The main aspect is to choose the diameter of the wire and the spring’s stiffness that the desired external force can be generated by the wire without crossing a defined stress level. That guarantees the actuation durability of the wire.

Modelling

To model SMA-actuators there are different approaches. The beginning reported in [4] constrains the mathematical approach to the inner behavior of the material. This yields physically defined model parameters, which can be measured or are given in the material specification. Therefore it is suitable to create a model for control design purposes. Based on that approach Fraunhofer IWU developed a Matlab®-based simulation tool to emulate the properties of an SMA wire [5], [6]. The tool is based on the power balance of the wire actuator. The contained terms result of the characteristic material behavior combined with the thermal and mechanical boundary conditions. It can be described as

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

The energy input P_{el} 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 P_{therm}. 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 transition process, which is modeled by a finite state machine. That enables to change the phase transition process depending on rising or falling temperature. During the phase transition 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 numerical solved and correlates approximate with the results of the measurement. Due to the nonlinear effects and the occurring feedback loops it is rather not practicable to design a linear position controller. An effective control design necessitates a linear description of the control plant. Due to the thermal hysteresis a linearization of the model at a defined work-point is not possible. Instead the approach given in [3], [6] is used. It exploits a piece-wise linear hysteresis description of the material's hysteretic behavior to define different models for different actuator states (actuator whilst phase transformation and actuator beyond phase transformation). Combined with a linear approach for the convection heat, neglecting the mechanical power, a linear system description in the Laplace-domain can be derived:

$$\Delta\vartheta(s) = \frac{1}{k_1 \cdot L_0} \cdot \frac{1}{1 + s \cdot T} \cdot P_{el}(s) \qquad (2)$$

This transfer function describes the wire's temperature ϑ and the wires deflection depending on the input power P_{el}. The behavior of the SMA-wire is represented by a first order lag-element with a time constant T:

$$T = \frac{m \cdot c_p}{k_1 \cdot L_0} = \frac{\pi \cdot c_p \cdot \rho \cdot d^2}{4 \cdot k_1} \qquad (3)$$

where ρ is the SMA's mass density, c_p the specific heat capacity and k_1 a constant describing the thermal convection. The wire's diameter d appears squared in the numerator of the term. That means increasing the diameter of the wire to reach higher actuation forces, will also result in a bigger delay of the transfer behavior. The design of the wire's diameter in fact has to be a compromise between the reachable forces and the reachable reaction speed.

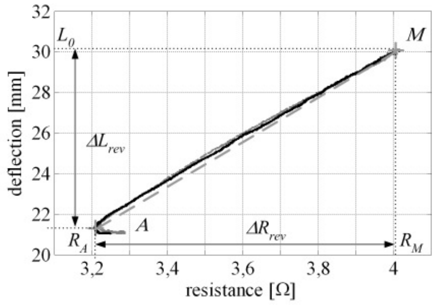

Fig 4: *Measured length-resistance-correlation (NiTiCu-wire Memry GmbH).*

Control Design

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 phase transition from the martensitic to the austenitic lattice and the so involved changes in the structure of the SMA-material, the status of transition correlates with the electrical resistance. In fact the lattice structure in the austenite state is more regular than in the 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.

The type of the length-resistance correlation strongly depends on the alloy composition. Measuring results of a ternary NiTiCu-wire shows an almost linear correlation without any hysteretic effects (see Fig 4). A linear approach is suitable to approximate this correlation:

$$L = L_0 - \frac{\Delta L_{rev}}{\Delta R_{rev}} \cdot (R_M - R) \cdot \qquad (4)$$

Here ΔL_{rev} and ΔR_{rev} are the maximal differences of the wire resistance and the achievable stroke during the phase transition (see Fig 4).

The plant only consists of a first order lag element that can be controlled by a simple PI-controller as written in Laplace-domain as:

$$G_C(s) = k_c \cdot \frac{(T_c s + 1)}{s} \cdot \qquad (5)$$

Choosing the controller time constant T_c to compensate the plants time constant T results for the closed loop in a first order lag-behavior without overshoot. The time constant of the closed loop can be adjusted in a wide range by changing the controller gain 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.

Results

The control algorithm described above, was implemented at a dSpace®-Rapid prototyping hardware. The controller parameters were directly determined using the simplified plant model, given in Eq. (2). No additional adjustments during implementation were necessary. The performance of the control loop was investigated by laboratory measurements and is shown in Fig 6. The maximal deviation occurs at the maximal actuator stroke and is about 5%. This is caused by the linear approximation of the stroke-resistance-correlation. Regarding Fig 4 it is obvious that near R_A the deviation of the approximation is maximum. However, grasping of different cylindrical bodies in two different ways is possible.

The actuation properties of the designed hand model are given in Table 1. The achievable gripping forces are comparatetively small. The reason therefore is the kinematics of the finger and, above all the diameter of the SMA-wire. Increasing the diameter certainly offers a higher level of gripping force, but will also slow-down the finger's speed. This is no problem during bending operation, whilst the actuator is heated, an acceleration of the heating process can be achieved by increasing the heating power. It is rather a problem whilst the wire has to cool down. The used passive cooling approach doesn't offer a chance to fasten the cooling process.

Fig 5: Hand model grasping a cylindrical body.

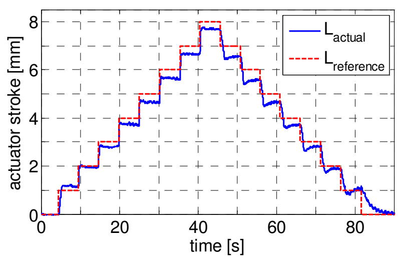

Fig 6: Position control performance.

Gripping force - between thump and fore finger - between middle/ring finger and metacarpal	 0.4N 1.2N
Speed - bending (active heating) - stretching (passive cooling)	 60°/s 10°/s
Power consumption (per finger) - Maximum (fast moving) - holding position	 5W 1W
Positioning error	<5°

Table 1: Properties of the hand model

In conclusion the main appraisal is that passive cooled SMA-wires are not suitable for complete drive system of hand prosthesis. Nevertheless, theirs high specific workload and the working principle close to human muscles possess to design very simple and easy to integrate position controlled drives. That offers the chance to enhance electrical driven prosthetic devices by implementing additional degrees of freedom without needs for additional cross-section and additional weight.

References

[1] Hoffmann, K.-P., M. C. Carrozza, S. Micera, K. P. Koch, K. Yoshida, R. Ruff.: Die fühlende Handprothese – ein Projekt mit Zukunft, Orthopädie-Technik 8/07, S. 564 – 570

[2] Mounier, S.: Entwicklung einer realitätsnahen Kraftrückkopplung bei fluidisch betriebenen Handprothesen, Dissertation, Fakultät Maschinenbau, Universität Karlsruhe, 2004

[3] Jung, J. :Aufbau eines Greifmechanismus mit FG-Drahtaktoren. Diploma-Thesis, Technische Universität Dresden, (2009)

[4] Oelschlaeger, L.: Numerische Modellierung des Aktivierungsverhaltens von Formgedaechtnisaktoren am Beispiel eines Schritt-antriebes. Ruhr-Universitaet Bochum, Lehrstuhl fuer Produktionssysteme, Dissertation, 2004

[5] Bucht, A., Pagel, K., Jung, J., Numerische Simulation des Aktivierungsverhaltens von thermischen Formgedächtnislegierungen, Model-Based Design Forum, Darmstadt, (2009)

[6] Neugebauer, R., Bucht, A., Pagel, K., Jung, J.,: Numerical simulation of the activation behavior of thermal shape memory alloys, Industrial and commercial applications of Smart Structures Technologies, Proc. of SPIE, San Diego, CA, 09.03. 2010,

[7] Czechowicz A., Meier H., Dilthey S., "Regeln von FG-Legierungen mit Widerstandsrückkopplung" Mechatronik, 11-12/2008, p. 24-27 (2008)