Control Approach for a Novel High Power-to-Weight Robotic Actuator Scalable in Force and Length

Robert Kratz, Maximilian Stelzer, Martin Friedmann, and Oskar von Stryk, *Member, IEEE*

***Abstract*— The development of a control approach for a novel, soundless, lightweight and multifunctional shape memory alloy (SMA) actuator scalable in force and length for personal assistance or home-help robots is presented in this paper. The SMA actuator is based on lightweight bundles of thin wires of prestrained shape memory alloy that change their length when heated above their transformation temperature. The design approach of the actuator allows arranging the point of actuation in any direction and ensures a short cool down time to guarantee a frequency of contraction/stress cycles that is high enough to allow fast joint motions. This is needed for the generation of fast joint motions. For the use of the actuator the novel control approach has been experimentally validated. The approach uses the resistance of the actuator as a linear position encoder and there are no additional external sensors needed. The application of the new actuator to a novel lightweight humanoid robot is outlined. One advantage of the actuator over electric motors lies in the large variety of user-defined points of actuation of the in pull-force and length free scalable actuators and the high power-to-weight ratio. The results demonstrate that it is possible to build a large humanoid robot actuated with SMA actuator in a new way.**

I. Introduction

PRESTRAINED shape memory alloys (SMAs) change their length when they are heated above their transformation temperature. This simple working principle of SMA has made it attractive for various miniaturized devices [1]. Prestrained SMAs like Nickel-Titan can change their length up to 8% when heated [2]. Based on this property various micro-technical actuators have been developed in the past [3,4]. In this paper, the development of a control approach for a novel SMA-actuator for robots is presented. The novel actuator is made of a serial-parallel connection of Nickel-Titan (NiTi-) wires [5] instead of only a parallel connections of the wires [6, 7, 8]. The actuator is scalable in force and length and allows the point of actuation to be arranged in any direction.

In general, the material behavior of shape memory alloys is nonlinear and hysteretical caused by the property of the material. To design a macroscopic SMA actuator necessitates the development of a model that characterizes the nonlinearities and the hysteresis in the used materials. The control approach described in this paper is able to compensate these hysteresis effects. This is possible by a new model that allows using the actuator as a linear position encoder and force sensor at the same time. The sensor information can in addition be used, e.g., to identify the weight of a lifted load.

R. Kratz, M. Stelzer, M. Friedmann, and O. von Stryk are with the Simulation, Systems Optimization and Robotics Group, Department of Computer Science, Technische Universität Darmstadt, Hochschulstr. 10, D-64289 Darmstadt, Germany (phone: +49-6151-164899, fax: +49-6151-6648, e-mail: {kratz, stelzer, friedmann, stryk}@sim.tu-darmstadt.de, web: www.sim.tu-darmstadt.de).

II. Actuator Design and Measurement

The design of a macroscopic SMA actuator has to account for the time needed for one contraction/stress cycle. A SMA element is usually heated by passing an electric current through it and cooled by the heat transfer to the environment. The maximum force of a SMA-wire is directly proportional to its diameter. To use SMA as an actuator for (humanoid) robots high forces are needed, but the cycle time of the actuator also highly increases with the wire's diameter. To avoid this property the new actuator/sensor design presented in this paper combines many single SMA wires in a new way to one muscle-like actuator. A wide field of possible applications is a primary goal of the actuator design. By keeping a minimum distance between each single wire, a short cool-down time of the thin wires can be ensured for the entire actuator.

Commonly, the construction of the SMA wire bundle consists of a multitude of wires in parallel attached to a bracket by crimps at the both ends of the actuator. This should preserve the contraction properties of the wires [6]. One way to raise the pull force of the actuator is the combination of wires with different diameters [7]. The bundles of Ni-Ti-wires are attached to the device with a cable at both ends. One end is moveable and one stationary to move the device.

To advance the SMA actuator design a plastic cylinder is tapped and the SMA wire is wrapped around. Thereby a parallel serial connection of the wires can be realized and a constant distance between all wires is guaranteed. In addition the cylinders can be used as a mounting part for the actuator [5].

Using two of these actuators in an antagonistic flexor-extensor actuator-like manner offers the possibility to generate a defined force at every time. Another possibility is to use a spring in combination with one SMA actuator.

One advantage of this new design is the scalability of pull force and length. The number of wires determines the pull force. One type of actuator used in the experiments is made up of 10 pairs of SMA wires with a thickness of 100μm and 180gf pull-force each (Fig. 1). The total pull

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force is 3.6kgf. The actuator has a length of 22cm and a maximal displacement of 1.5cm.

Fig. 1. The developed SMA wire bundle actuator.

III. EXPERIMENTAL HARDWARE

The use of macroscopic SMA actuators needs a complex nonlinear control approach. Theories for control found in literature are: neural fuzzy, dissipativity, variable structure control and segmented binary control [8,9,10].

The novel control approach presented in this paper is based on the hypothesis of a decreasing resistance of the actuator during contraction and that a certain position has a reproducible resistance. Based on this assumption, the resistance can be used as a linear position encoder. Thus there is no need for external position sensors.

The resistance can also be used for an optimal heating and to prevent overheating and thereby also burn out of the actuator [11]. This is not yet used in the experiments.

The amount of current needed to contract the actuator and the time needed to contract gives information about the pull-force. Heavier loads need more energy and therefore a higher current to contract than a light load.

The experimental rig consists of an actuator fixed in the centre of the top bar. A platform to place different weights is base-fixed at the actuator followed by an inductive linear position encoder used for evaluation of the resistance-based position encoding.

There is the option to fix a second actuator from the bottom of the rig to the position encoder. A regulated power supply is provided by the use of a pulse width modulation.

IV. MEASUREMENT

To get the relation between resistance and contraction the platform was loaded with different weights. Also the current to heat the actuator was varied at each weight. The actuator has a length of 22cm and a maximum contraction of 1.7cm. The results show that there is a close relation between the resistance and contraction (Fig. 3).

In addition the results show that the relation between resistance and contraction is independent of the load and depends only on the applied current [5]. The curve of the resistance is inverted and scaled in the diagram to fit to the contraction curve. The change in the resistor curve after 65s is related to a temperature higher than 90°C.

The interrelation between current and resistance is linear and can be retrieved easily. The total change of the actuator's resistance between the contracted and elongated state is 0.711Ω and the values can be reproduced to a deviation of 0.002Ω. These results have been presented in [15].

To arrange the fixing of the actuator in any direction there is a need to look at the behavior of the actuator with shifted/rotated fixing. Therefore one end of the actuator

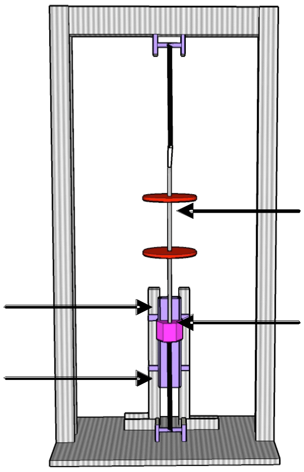

Fig. 2. Experimental rig.

was fixed at the experimental rig (cf. Fig. 2) and the other end moved. The measurement has shown that twisting the fixing up to 90° does not lead to different actuator behavior.

It is possible as well to shift the fixing up to a difference up to 50mm by a total length of the actuator of 22cm. The elasticity of each single wire compensates the different strains of the whole actuator. The experiments show that

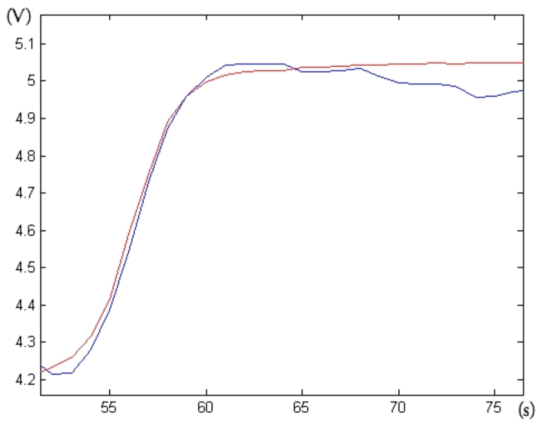

Fig. 3. Relation between resistance (4.2V ~ 8.2Ω, 5.0V ~ 7.5Ω,) and contraction (4.2V ~ 22cm, 5V ~ 20.3cm) (contraction: red line, resistance: blue line)

the actuator can be used to generate rotary motion. With use of the resistance there is no need for additional position sensors.

V. ELECTRONICS

To access a certain intermediate position between total contraction and strain with the actuator a low energy consuming power electronics and an electronics that is able to measure the resistance of the actuator has been developed.

The electronics is divided into three groups. A *microcontroller* receives the information about the desired position from a *host computer*, e.g., in humanoid robots from an embedded PC. In the microcontroller the regulation algorithm is implemented that triggers field effect transistors at the *power electronics*.

A. Power Electronics

To reduce the power consumption the actuator power supply is realized by a pulse width modulation. Therefore a field effect transistor (FET) is triggered to provide a pulse width modulation. The gate is connected to ground via a 10kΩ resistor to have a defined state all the time. A 1Ω measuring resistor is placed between drain and ground to obtain the current flowing by measuring the voltage drop over the resistor. This layout is needed for every single controlled actuator.

B. Microelectronics

To provide a real-time control for the novel actuator a microcontroller circuit has been developed. The core of this circuit is an Atmega32 device from Atmel Cooperation running at 16MHz. One controller is capable of controlling up to 8 actuators.

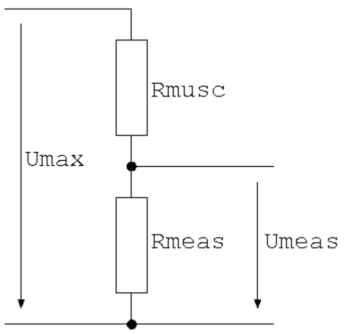

Fig. 4: Indirect measuring of actuator's current.

To control an actuator, one digital channel is used to generate a pulse-width-modulated (PWM) signal. The signal's frequency is 1000 Hz; the pulse-width is adjustable in steps of 1%. Thus the average operating voltage of an actuator is proportional to the pulse width.

The current of each actuator is measured indirectly by means of the voltage drop U_{meas} on the actuator's measuring-resistor (Fig. 4), which is measured by one of the 8 analog-digital-converters (ADC) of the microcontroller. To get comparable values by varying pulse width the PWM signal is replaced by always the same high value during measurement. Thus the voltage drop over actuator and actuator measuring-resistor is always the actuators full operating voltage U_{max} and the ADC's resolution can be used optimally.

This measurement is performed at a rate of 100 Hz. To allow U_{meas} to settle the measurement is performed 60 microseconds after switching on the actuator's voltage. Without settling down the voltage of the actuator the measured values might be incorrect. The generation of this measuring-signal is independent of the generation of the pwm signal. As the signal is comparably short, the average voltage of the actuator is changed by less than 1%, which easily is compensated by the control algorithm described in section VI.

The current flowing through actuator and measuring resistor is given by the equation $I_{meas} = U_{meas}/R_{meas}$, where R_{meas} is the resistance of the measurement resistor. The actuator's resistance can then be calculated easily by $R_{musc} = (U_{max} - U_{meas})/I_{meas}$.

After performing the measurement for an actuator, the actuator's control-algorithm described in Section VI is executed.

The control circuit communicates with a host computer by RS-232. More than one circuit can be used in parallel using the same connection sharing the same sending and receiving lines. To accomplish this, the sending lines of the single circuits have been decoupled using diodes forming a logical "or". The receiving lines of all circuits are used in parallel; each device has a unique ID number to filter messages. To control more actuators the use of only one RS-232-connection is necessary. When controlling for example 40 actuators in parallel, it is possible to send a new desired value to each actuator every 20 milliseconds. Additionally an inter-circuit communication using a two-wire serial-connection between the microcontrollers can be established. This might be helpful using offsets generated by gyroscope-values.

Depending on the current application, other tasks can be accomplished by the microcontroller. In the author's group reading gyroscope-values for stability control as well as generation of control-signals for servos have been implemented for humanoid robots. These applications can be run in parallel with the control of the actuators.

VI. CONTROL APPROACHES AND RESULTS

A. Control Approaches

Control of the actuators was investigated for linear actuator movements on the test rack (see Section III). Linear motion of only one actuator was investigated, i.e. the antagonist-protagonist mechanism was not used for this first experiments.

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Control for each of the approaches was tested with different test weights and a constant voltage of 18 V. Current was set by pulse widths sent to each of the actuators (Section V).

The first approach of controlling the actuator is using an integral controller, i.e., the desired resistance is increased resp. decreased when the actuator was too short resp. too long. This resulted in oscillations of the length of the actuator because the time for heating the actuator was relatively long and still after reaching the desired position and thus stopping increasing current, the actuators kept on increasing their temperature caused by a time-delay of the actuator. The amplitude of the oscillations is of the magnitude of some millimeters (and relatively about up to 15%) and thus not acceptable.

The second approach is to use a defined pulse width as long as the actuator is too long and zero pulse width as soon as the actuator reaches its desired position. This also results in oscillations of the actuator of about 5% around the desired position. One problem with this approach is in addition, that to start the contraction of the actuator, it has to be warmed from surrounding temperature, which results in a large time needed for shortening. This problem is solved by sending a pulse width of 10% for non-acting actuators instead of zero to get a defined pre-heating next to the activation temperature of the actuator. This effect of a faster reaction was already shown in general by the authors in [5].

The third approach is a modification of the second one. To reduce the oscillation around the target position an offset is integrated in the control approach. The used shape memory metal NiTinol has a strong characteristic hysteresis curve. Similar to the offset to heat the actuator next to the activation temperature we implemented an offset for the regulation. A constant current of 15% of the maximum current of 2.5A is combined with the second regulation approach. To be able to ignore the hysteresis effects, which are independent of the load [6] but depend on the applied current, the resistance is measured with the first PW-signal of an interval that applies a constant current.

In this case the regulation is about 2% accurate compared of the total possible contraction length. This control approach has been used in the experiments of the following subsection.

B. *Experimental Results*

The developed control algorithm is based on the use of the resistance as a linear position encoder. The regulation is able to move the actuator to a certain position and hold this position. The use of the actuator and the control approach in (e.g., humanoid) robots necessitates in addition that changing stresses can be compensated automatically. In Fig. 6 the position of the actuator measured by an external inductive position encoder is shown. The resistance of the actuator can be compared with the real position in Fig. 5. The current triggered by the control approach is shown in Fig. 7.

For testing the control approach the set up contains one actuator with a length of 22cm containing 20 pairs of

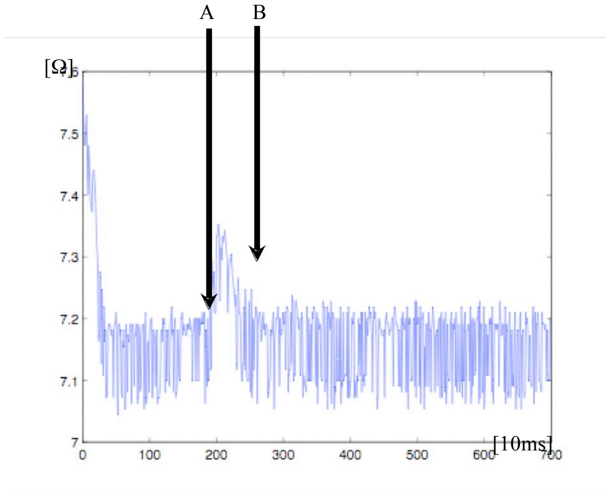

Fig. 5: Measured resistance of the actuator.

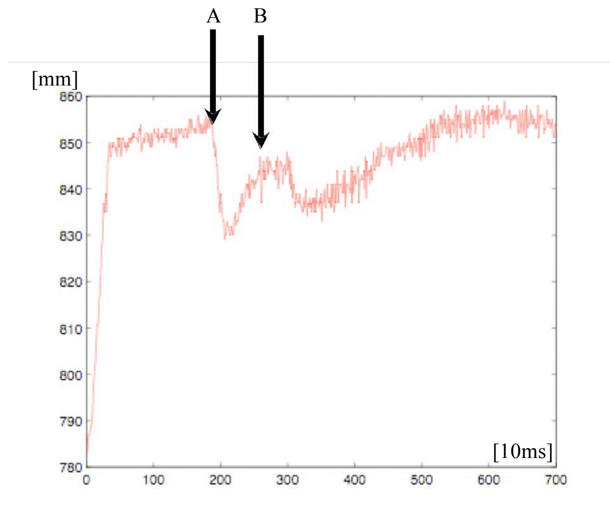

Fig. 6: Position measured with an external position encoder.

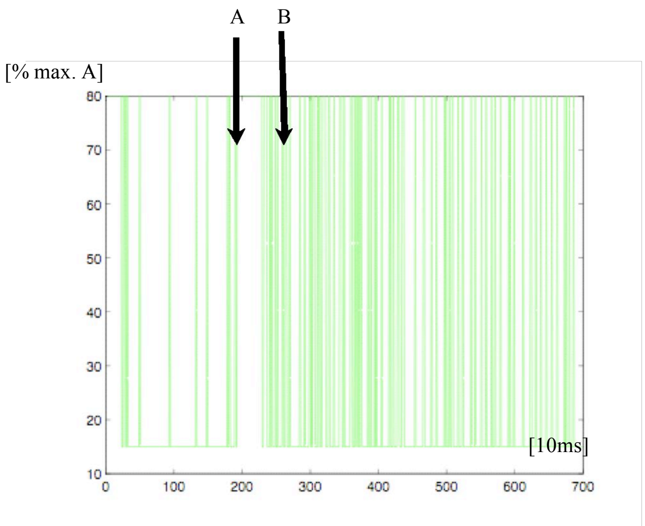

Fig. 7: Current triggered by the pulse width modulation.

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NiTinol wire. The actuator was preloaded with 1kgf.

The target resistance for the control approach was 7.2Ω. As shown in Fig.5 at the beginning of the adjustment control the actuator reaches its target position fast. As long as the measured resistance is higher than the target resistance the regulation heats up the wire with the maximum current. After reaching the position the current is reduced to the offset.

After 2 seconds the actuator was strained at the experimental rig (Fig. 2) with an additional load of 1kgf (A). Caused by the higher force needed the actuator left its controlled position and got stressed. Directly with the stress of the actuator the control raised the amount of pulse width to get back to its target position. The second stress (B) within the stress-cycle is cause by the method of loading the actuator. In this experiment the authors loaded the platform by hand, so the additional pull force changed reproducible always two times. One time while lifting the weight onto the platform of the experimental rig and again when the load was released by the author's hand. After loading the platform, the actuator contracts more than its desired position before it becomes stable at its target value. The reaction time of the actuator to contract is very fast. E.g., to contract the actuator completely requiresless than 10ms, but the cool down time is about 10 times higher.

C. *Discussion*

The experiments demonstrate that it is possible to move the actuator to a certain intermediate position using the described control approach. Furthermore, the actuator can return to its initial position even if the pull force is changing. The oscillation of the resistor between 7.2Ω and 7.1Ω is caused by the fast measurement cycles and could be reduced by a measurement time higher than 60 microseconds. But the effect has no impact on the control approach because only a higher resistance would lead to a higher current and a shift in the actuator's position.

The time needed to return to a position after a change in pull force is still quite long. But the extreme change of force simulated in the experiments is unusual for many applications, like grippers, in practice. As shown in Figs. 4, 5, and 6 the control approach has to be improved further to reduce the reaction time to changing force.

The novel actuator with its control approach is much lighter than comparable servomotors. It has a weight of 20g and a pull force of 3.6kg.

VII. Conclusions and Outlook

A control approach for a novel SMA wire bundle actuator which may serve as the basis for artificial muscles of a humanoid robot has been developed and tested. It provides a large possible field of application in humanoid robotics.

An application to demonstrate the new control approach of the novel actuator/sensor design is the actuation of the humanoid robot Lara. Lara is 130cm tall and has a total weight of about 6.5kg including electronic and batteries (Figs. 8 and 9).

At first a skeleton of two legs, two arms and a hip has been built providing the needed degrees of freedom for humanoid walking. Thirteen actuators have been arranged in each leg and six in each arm for this purpose. The arrangement of the points of actuation has more freedom for the new actuator than for electric motors that are placed in the actuated, rotational joints in almost all currently successfully walking humanoid robots.

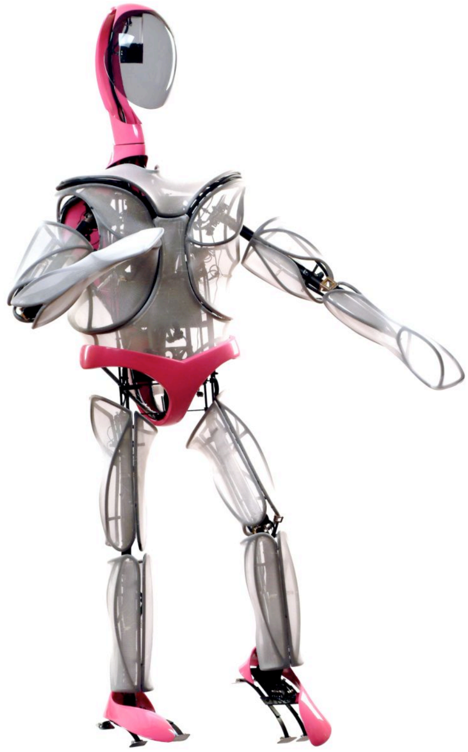

Fig. 8: Humanoid robot "Lara" actuated by 34 SMA wire bundle actuators (cf. www.lara-robot.de).

In addition, the novel actuator system enables a more lightweight robot design. The weight of Lara is about 1/6th of a comparable conventional robot actuated with electric rotary motors. This lighter design is compensating the less power efficiency of the SMA actuators working principle compared with electric motors. Furthermore, if new requirements are given for the actuation of a certain robot joint either one of the existing actuators can be changed or an additional actuator can be added easily.

The control approach still has to be improved to reduce the power consumption, but the regulation is about 2% of the total possible contraction length accurate. This is not the target accuracy but sufficient for many types of motions.

At the moment Lara is able to stand on one leg, to kick a ball and to move several steps in a mobile test rack. Caused by the light actuators her legs are able to swing. Next planned steps include the realization of autonomous bipedal

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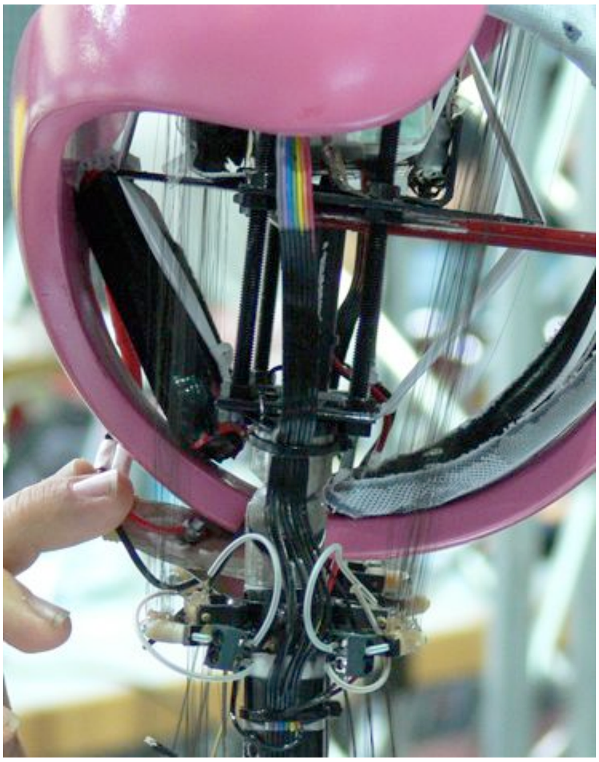

Fig. 9: Actuators integrated in the humanoid robot Lara.

walking and the development of a hand with fingers for the robot. For this purpose, the position accuracy of the control approach must be improved. To realize this, it is planned to advance the control algorithm, especially a detailed relation between force and current has to be derived.

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