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Control Approach for a Novel High Power-To-Weight Ratio Actuator Scalable in Force and Length for Robots

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***Abstract* - One of the research goals in robotics is the development of home-help robots. The development of a control approach for a novel lightweight and multifunctional shape memory alloy (SMA) actuator scalable in force and length for robots is presented in this paper. The SMA actuator is based on lightweight bundles of thin wires of prestrainend 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 result show that it is possible to build a large humanoid robot actuated with SMA actuator in a new way.

Index Terms – sensor systems, smart sensors, artificial muscles

I. Introduction

Prestrainend 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]. Prestrainend 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 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 a parallel connections of the wires only [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 non-linear and hysteretical caused by the property of the material. To design a macroscopic SMA actuators 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 hystereses 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 to identify e.g. the weight of a load lifted.

II. ACTUATOR DESIGN AND MEASUREMENT

The design of a macroscopic SMA actuator has to deal with 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 proportional to its diameter. To use SMA as an actuator for (humanoid) robots high forces are needed, but the cycle time of the actuator 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 high possible field of application is one of the primary object targets. 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]

Fig. 1: Picture of the actuator

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

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, 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 burn out of the actuator [11] in addition. This is not 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 and the current to heat the actuator was varied at each weight. The actuator has a length of 22cm and a max. 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.

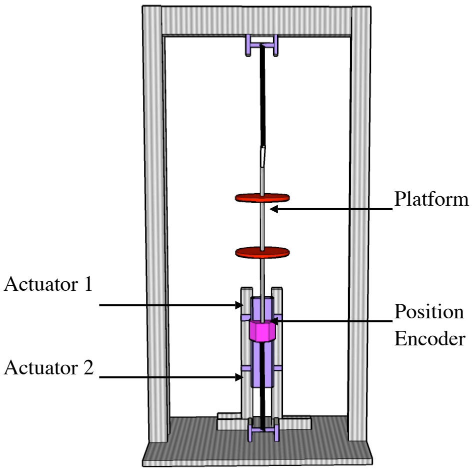

Fig. 2: Experimental rig

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 are presented in [12]

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. The measurements has shown, that twisting the fixing up to 90° does not lead to different actuator behavior. As well it is possible 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 the actuator can be used to generate rotary motion. With the use of the resistance there is no need for additional position sensors.

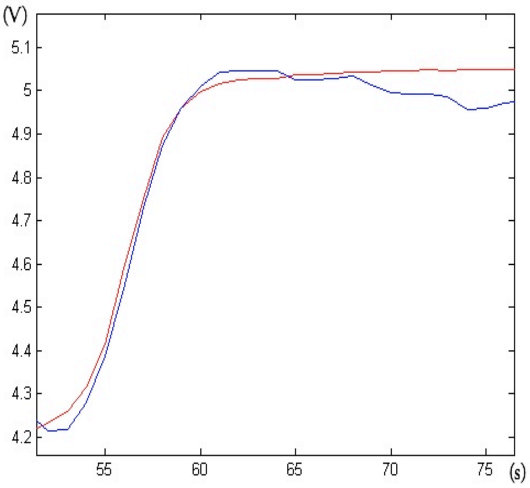

Fig. 3: Connection between resistance [4.2V = 8.2Ω, 5.0V = 7.5Ω] and contraction [4.2V = 22cm, 5V = 20.3cm] (contraction red line, resistance blue line)

V. ELECTRONIC

To access a certain intermediate position between total contraction and strain with the actuator a low energy consuming power electronic and an electronic that is able to measure the resistance of the actuator has been developed.
The electronic is divided into three groups. A *micro-controller* gets the information about the desired position from a *host computer* e.g. in humanoid robots from a Pocket PC. In the micro-controller the regulation algorithm is implemented that triggers field effect transistors at the *power electronic*.

A. Power Electronic

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 get the current flowing by measure the voltage drop over the resistor.
This build-up is needed for every single controlled actuator.

B. Microelectronic

To provide a real-time control for the novel actuator a micro-controller-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 actuator.

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 a 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 micro-controller. 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 best.

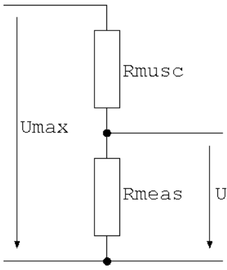

Fig. 4: Indirect measuring of actuator´s current

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, so that the actuator's resistance than can be calculated easily by $R_{musc}= (U_{max} - U_{meas})/I_{meas}$.

After performing the measurement for a 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 micro-controllers 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 micro-controller. In the author's group reading gyroscope-values for stability control as well as generation of control-signals for servos have been implemented. 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.

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).

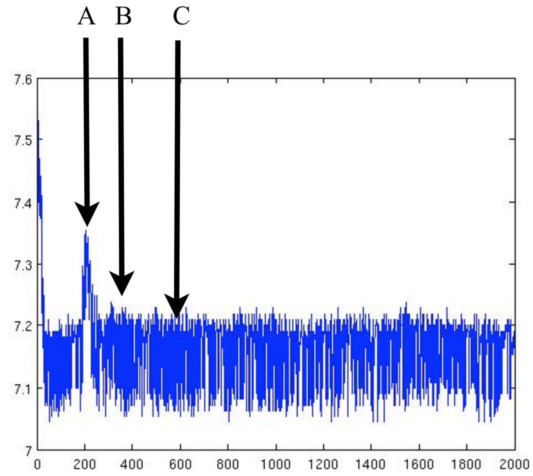

Fig. 5: The resistance of the actuator (in V and 10ms)

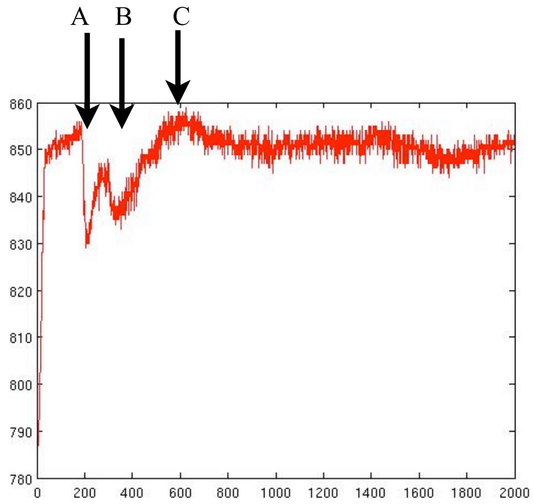

Fig. 6: Position measured with an external position encoder (in V and 10ms)

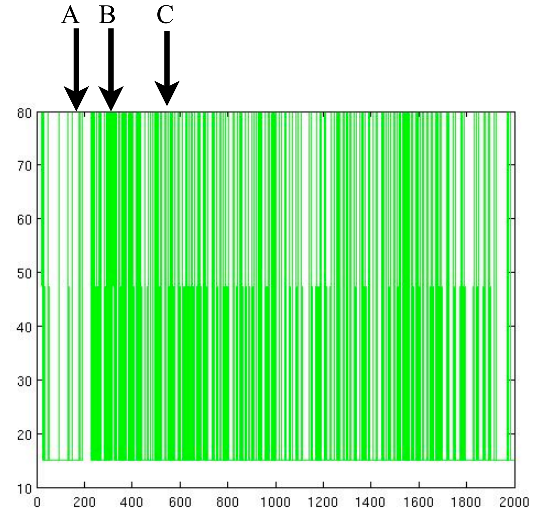

Fig. 7: Current triggered by the pulse width modulation (in % of max. Ampere and 10ms)

The first approach of controlling the actuator is using an integral controller, i.e. the desired resistance is increased resp. decreased while 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 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 in the order of 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 reached 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 high 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 be able to ignore the hystereses effects, which are independent of the load [6] but depends on the applied current, the resistance is measured with the first pw-signal of a interval that applies a constant current.
In this case the regulation is about 2% exact compared of the total possible contraction length.

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 (humanoid) robots necessitates in addition that changing stresses can be compensated automatically. In Fig. 6 the position of the actuator measured by an external 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 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 reached 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 his 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 of the authors hand. After loading the platform, the actuator contracts more than its desired position (C) 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 totally is less than 10ms, but the cool down time is about 10 times higher.

C. Discussion

The experiments show, that it is possible to move the actuator to a certain intermediate position using the described control approach. Further in 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 higher current and a shift in the actuator´s position.

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

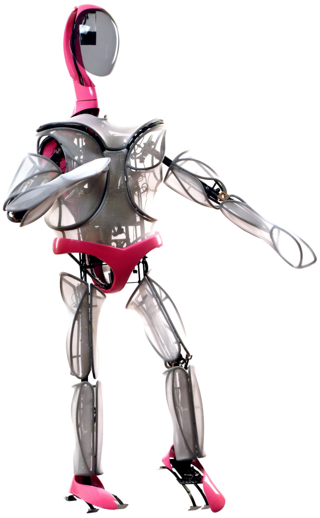

Fig. 9: Humanoid robot „Lara“ actuated by 34 SMA-actuators

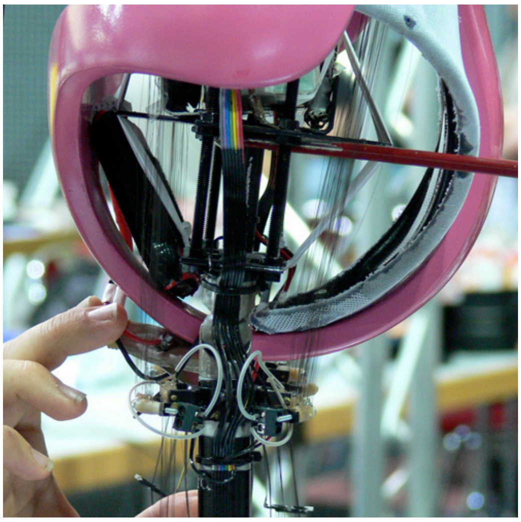

Fig. 10: Actuators integrated in the humanoid robot Lara

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

VII CONCLUSION AND FUTURE WORK

A novel SMA wire bundle actuator has been implemented into a test rack as the basis for artificial actuators of a humanoid robot.It provides a large possible field of application in humanoid robotics.

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

At first a skeleton of two legs, two arms and a hip has been built providing the needed degrees of freedom for bipedal walking. Thirteen actuators have been arranged in each leg, 6 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 joints in almost all currently successfully walking humanoid robots.

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 servomotors. This lighter design is compensating the less power efficiency of the SMA-actuators working principle compared with servomotors. 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 should be optimized to reduce the power consumption, but the regulation is about 2% of the total possible contraction length exact. This is not the target value but enough for many motions.

At the moment Lara is able to stand on one leg and kick a ball. Caused by the light actuators her legs are able to swing. Next planned steps are the realization of a bipedal walking and the development of hand with fingers for the robot. Therefore the control approach has to be more exact. 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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