A Modular, Energy Efficient Actuator Based on Magnetic Shape Memory Alloys

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Abstract:
Magnetic shape memory (MSM) alloys react to magnetic excitation with a deformation up to 6%, according to recent publications also up to 12%, and are a promising candidate for applications such as positioning, robotics and valve technology. In this work we describe, characterize and test a mechatronic system based on MSM alloys which entails a *push-push* actuating unit. The overall actuation system consists of a series of MAGNETOSHAPE® MSM modules that can be activated independently, and that can be composed and connected in different ways depending on the application needs. The actuated displacement is measured indirectly by a Hall sensor which is integrated in the actuator design. Each module is activated by a current source which is controlled by an algorithm running on a micro-controller. This algorithm is able to guarantee fast rise times and precise tracking of constant position references; moreover, it is able to offer a strong reduction of the power losses by a strategy which exploits advantageous properties of the hysteresis of the MSM alloys.

Keywords: Magnetic shape memory, energy efficiency, hysteresis, position control, PID control

Introduction

In recent years, magnetic shape memory (MSM) alloys have attracted scientific research due to their interesting properties. Several technical solutions based on MSM alloys have been proposed, ranging from sensors and energy harvesters to motion actuators. Among those, the push-push actuator (PPA) [1], usually composed of two MSM elements which work antagonistically, is particularly interesting because it offers electrically controlled displacements and the possibility of reducing the input energy when holding a constant displacement value (self-supporting property [2]).
In this paper, we describe and characterize a modular PPA designed with independent MSM modules, which can be interconnected to satisfy the application needs, producing motion in the vertical or horizontal direction. The modular PPA integrates a cheap, effective sensing unit to measure the displacement of its moving rod.
The integrated sensor provides the feedback information to the position control algorithm. Based on recent works [3], [4], the controller proposed in this paper exploits the self-supporting property of MSM alloys in order to reduce the current, thus the Joule losses and the heating in the actuator and in the power electronics.

A modular, flexible push-push actuator concept

Instead of using only two single MSM elements, the modular PPA makes use of two *groups* of MSM *modules*, A and B, arranged antagonistically, as illustrated by the schema of Fig. 1. Each group is composed by n MSM modules in series; the *j-th* module is a mechanical and electrical unit which entails and drives the *j-th* MSM element. The modules are mechanically interconnected in such a way that the strain of one MSM element (along x) can sum to the strain of another element of the same group. The module j converts the input current into the magnetic field that excites the *j-th* MSM element. The input current is provided by the *j-th* independent voltage-controlled current-source designed to cope with the resistance and inductance of module j. As a choice but not a restriction, the modules of group A are driven with the same input current i_{A}, and the modules of group B are driven with i_{B}, i.e., $i_{\mathrm{Aj}} = i_{\mathrm{A}}$ and $i_{\mathrm{Bj}} = i_{\mathrm{B}}$, $j = 1...n$. Since each module of one group is driven by the same current, we can state that a group is excited by the same field, i.e., $H_{\mathrm{A}j}(i_{\mathrm{A}}) = H_{\mathrm{A}}$, $H_{\mathrm{B}j}(i_{\mathrm{B}}) = H_{\mathrm{B}}, j = 1...n$.

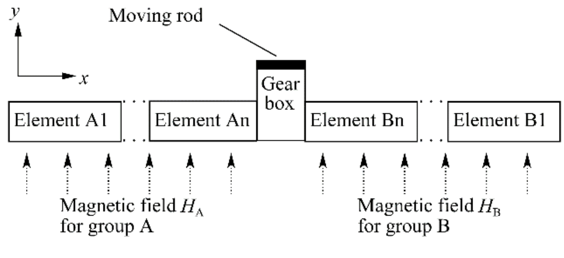

Fig. 1. *Schema of a modular, flexible push-push actuator*

The movement of the elements along x can be shifted along y by means of an optional gearbox that finally transfers the motion to the moving rod (see Fig. 1). The gearbox can be designed to scale strains and forces produced by the elements and to adjust their directions, thus addressing in a flexible manner a specific application.

The laboratory set-up of the modular PPA

Fig. 2 shows our laboratory set-up of a modular PPA. The actuator is built with standard MSM modules, each entailing a MAGNETOSHAPE® MSM element with $2\times3\times15\ \mathrm{mm}^3$ that produces 6 % free strain (0.9 mm of elongation). The elongations of the elements add to the horizontal stroke of the complete actuation device, in this case up to 1.8 mm. Each module is characterized by a resistance of $2\,\Omega$ and an inductance of $5\ \mathrm{mH}$.

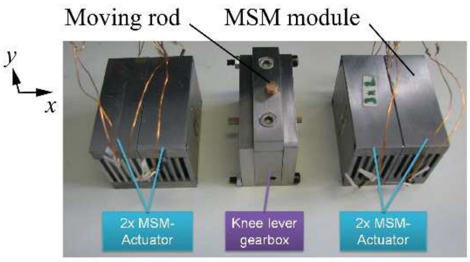

Fig. 2. *Laboratory set-up of modular PPA*

Between group A and group B, a knee lever is mounted that mediates the interaction between the actuation groups and simultaneously allows transition of the elongation orthogonal (along y) to the effective direction of motion of the MSM elements (x) with a variable gain ratio.

The gain ratio of knee levers depends on the position of the lever. Close to maximum stroke, the force amplification and the strain reduction are maximal, whereas at minimum stroke the force amplification and strain reduction are minimal. This partially compensates the general tendency of decreasing magneto-force output of MSM elements with increasing elongation. Here we have chosen a knee lever with a force amplification ratio of 2:1. As shown in Fig. 3, the force-stroke behaviour of only one pair of modules, measured with the knee lever gearbox attached, produces a large amount of externally usable force (the upper branches are measured with actuator modules energized with 6 A).

The return force of about 5 N is nearly constant over the complete strain (the lower hysteresis branches in Fig. 3 are measured without energizing the MSM modules, $i_A = i_B = 0$), meaning that external forces up to 5 N do not affect the position of the moving rod when the power supply is off (self-supporting property [2]).

To measure the position, the moving rod is equipped with a permanent magnet, which provides a bias magnetic field to a Hall flux-density sensor (integrated in the actuator design). The Hall sensor measures the position dependent stray field of the permanent magnet and outputs a corresponding voltage, which is used for feedback control purposes. Other sensing solutions based on self-sensing [5] or on resistance measurement [6] were not considered because not suitable for the modularity of the actuator, or because insufficiently robust for commercial applications. The sensing system was designed to measure the position with a resolution of about 2 µm.

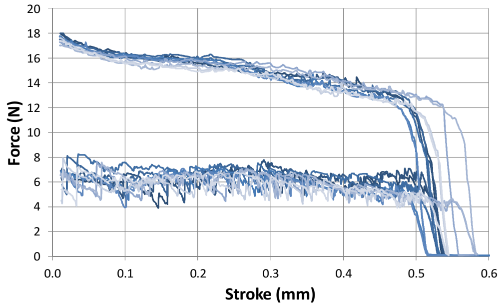

Fig. 3. *Force-stroke behavior of one pair of MSM modules with knee lever*

The Hall sensor and the bias magnet are arranged in such a way that the electromagnetic fields used to drive the MSM modules do not influence the measurement of the Hall sensor and, accordingly, the measurement of the displacement.

The chosen sensing solution is precise, low-cost, and fully compatible with the desired modularity and flexibility of the actuator.

Characterization

The described actuator provides positive or negative displacement when group A or group B is excited by a magnetic field, respectively. Fig. 4 shows the input-output hysteresis obtained by a decreasing sinusoidal input current with peak-to-peak amplitude of 6 A. The abscissa displays a logic current i: its positive values are provided to group A, and its negative values are provided (as positive) to group B. The measurement of the integrated Hall sensor is compared to the measurement performed by a commercially available laser triangulation sensor (Keyence LC-2220).

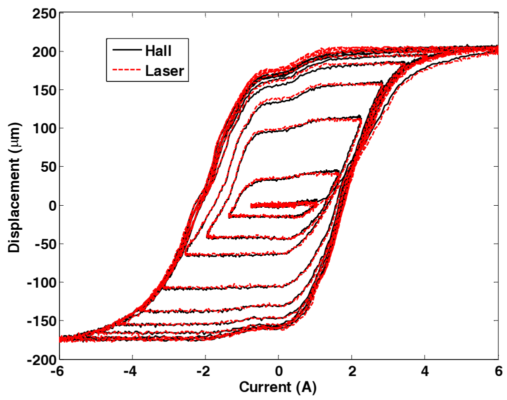

Fig. 4. *Displacement in response to a decreasing sinusoidal current with an initial amplitude of 6 A. The displacement estimated with the integrated Hall sensor is compared to the displacement measured by a triangulation laser sensor.*

Fig. 5 shows the displacement response for several current pulses of 5 A (duration 0.2 s) in the modules of group A and B. The currents i_A and i_B in the groups are displayed. It can be noted that the actuator is able to hold a position value when the currents are removed. This is coherent with the almost flat upper and lower hysteresis branches in Fig. 4.

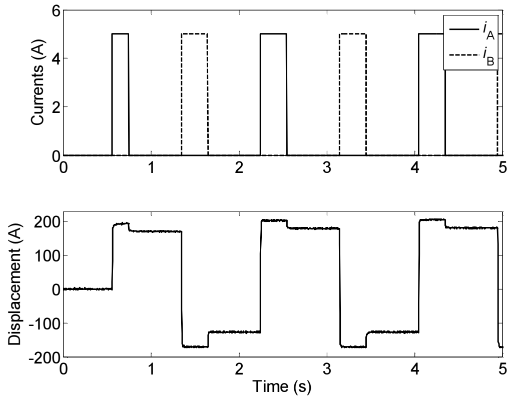

Fig. 5. *Displacement response to brief current steps of 5 A in group A and group B.*

Energy-efficient PI control of the PPA

Since several valid approaches for controller design already exist [4], here we focus on particular control strategies which improve the energy efficiency of an existing PI controller. For energy-efficiency we intend the reduction of Joule losses and heating phenomena in the actuator.

The following possibilities are proposed:

a. *Overshoot*. Refer to Fig. 4. One way to get to a displacement value r is to go beyond that value, and then reach it with a reduction of the current.
b. *Energy-efficient controller*. The controller can be equipped with an algorithm which smartly reduces the control current i whenever possible [7].

The strategies are fully compatible with the controller design procedure suggested in [4] and can be combined to obtain better energy performances. Strategy (a) is straightforward: it suffices to add a "fake" reference term $r_F(t)$ to the real one, where $r_F(t) \to 0$. Strategy (b) requires a novel mathematical formulation of the controller.

Let us consider a generic standard PI controller C, which provides an integral control action $\mu(t)$ and a proportional control contribution $k_1\tilde{y}(t)$,

$$\text{C:}\begin{cases} \dot{\mu}(t) = k_0\tilde{y}(t) \\ i(t) = \mu(t) + k_1\tilde{y}(t) \end{cases}, \qquad (1)$$

where $\tilde{y}(t) = y(t) - y_D(t)$ is the tracking error, $y(t)$ is the measured displacement of the PPA, $y_D(t) = r$ is a constant desired (reference) displacement, k_0 and k_1 are the integral and proportional gains, respectively. Note that $y_D(t)$ could contain the fake reference term if strategy (a) is used: in this case, $y_D(t) = r + r_F(t)$, where r is, as above, the reference to be finally tracked.

The knowledge given by the hysteresis of the PPA (see Fig. 4) is that the current *i(t)* can be reduced to some value without a significant displacement change. We propose an *energy efficient PI controller* Ce defined as:

$$\text{Ce:}\begin{cases} \dot{\mu}(t) = k_0\tilde{y}(t) - \kappa\exp(-\beta\tilde{y}^2(t))\mu(t)\ ,\ \kappa > 0 \\ i(t) = \mu(t) + k_1\tilde{y}(t) \end{cases}, \qquad (2)$$

where the term $-\kappa\exp(-\beta\tilde{y}^2(t))\mu(t)$ aims at reducing $|\mu(t)|$, once the error $|\tilde{y}(t)|$ falls below a threshold determined by the parameter $\beta > 0$, i.e. $\sqrt{4/\beta}$, so that the bigger β the smaller the error threshold. Briefly speaking, the energy efficient controller (2) tries to reduce (reset) the integral part of the current and does it when the error satisfies $|\tilde{y}(t)| < \sqrt{4/\beta}$; when not below the threshold, the controller (2) behaves almost as the standard counterpart (1) because $\exp(-\beta\tilde{y}^2(t)) \cong 0$ for $|\tilde{y}(t)| > \sqrt{4/\beta}$. Within the threshold, the reduction of $|\mu(t)|$ is determined by k_0 and κ. A bigger κ ensures a faster reduction of $|\mu(t)|$ when $|\tilde{y}(t)| < \sqrt{4/\beta}$.

Remark. The controller in (2) is an evolution of the integral-reset proposed in [3]. The main advantages are that (2) gives a mathematical way to define how the reset occurs and, more important, (2) does not require any a-priori characterization or knowledge of the hysteresis, because it reduces $\mu(t)$ whenever possible to a suitable value.

Experimental results

In this section we present the experimental results obtained with two standard PI controllers and their energy-efficient counterparts.

First of all, let us define formally the control energy required by the controller C as the integral of the square of the current (ISC) i used in the tracking task,

$$\text{ISC(C)} \triangleq \int_0^T i^2(t)\mathrm{d}t\ , \qquad (3)$$

where T is the duration of the task. The ISC relates to Joule losses in the PPA and is responsible for the size of all the driving electronics, and for the heating of the actuator and MSM elements.

We consider the controllers C1 and C2 described in (1), obtained with the design method in [4], and their energy-efficient versions C1e and C2e described in

(2), which combine strategies (a) and (b). The parameters are given in Table 1.

Fig. 6 compares the tracking performance of C1 and C1e: it can be noted that the tracking is almost identical, while the required currents are visibly different. The energy indices of the controllers are $\mathrm{ISC(C1)} = 46\ \mathrm{A^2 s}$ and $\mathrm{ISC(C1e)} = 17\ \mathrm{A^2 s}$, meaning that controller C1e reduces the Joule losses by 62%.

Fig. 7 compares C2 and C2e. Again, the tracking performance is very similar, while the currents are different. The indices are $\mathrm{ISC(C2)} = 19\ \mathrm{A^2 s}$ and $\mathrm{ISC(C2e)} = 12\ \mathrm{A^2 s}$, meaning that C2e reduces the Joule losses by 34%. However, the user can tune strategies (a) and (b) in order to maximize the energy efficiency for the particular application.

Conclusion

This paper describes a modular and flexible actuator based on magnetic shape memory alloys. The push-push unit is composed of independent modules that can be interconnected as desired, and features an integrated, low-cost and effective displacement sensing solution. In order to exploit the properties of MSM alloys, this paper proposes a novel control design, which reduces the required electrical power for certain positioning tasks. The proposed modular, flexible, integrated actuator solution offers rise times of less than 0.1 s, tracking errors of about 2 µm and reduction of power losses up to 60 % (compared to MSM actuators without self-supporting and without the proposed control strategy).

Aknowledgment

The authors would like to thank the DFG (German Research Foundation) for the partial support of our work with the Transfer Projekt “Development of a Magnetic Shape Memory Based Mechatronic System”.

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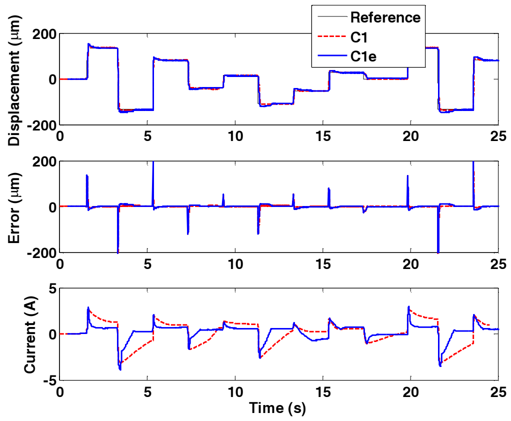

Fig. 6. *Comparison of C1 and C1e*

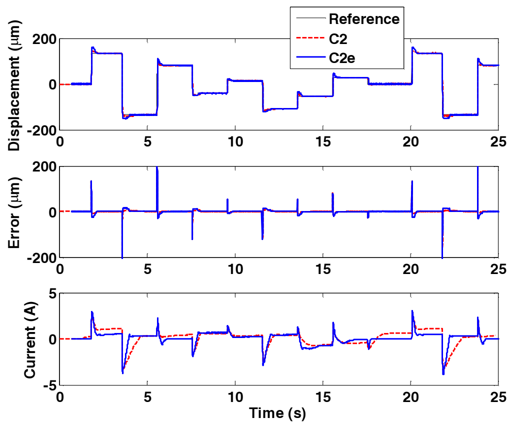

Fig. 7. *Comparison of C2 and C2e*

Table 1. *Controller parameters*

Controller name	Standard gains	Energy-efficient strategies
C1	$k_0 = 0.5$ A/s · µm $k_1 = 0.001$ A/µm	Not applied
C1e	$k_0 = 0.5$ A/s · µm $k_1 = 0.001$ A/µm	$\kappa = 50$ $\beta = 10$ $r_F(t) = 0.1 r \exp(-10t)$
C2	$k_0 = 1$ A/s · µm $k_1 = 0.001$ A/µm	Not applied
C2e	$k_0 = 1$ A/s · µm $k_1 = 0.001$ A/µm	$\kappa = 50$ $\beta = 10$ $r_F(t) = 0.1 r \exp(-10t)$