Design and Control of a Series of Linear and Rotary Actuators based on Shape Memory Alloy Wires

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Abstract: This paper introduces a family of modular electro-mechanical actuators based on Shape Memory Alloy (SMA) materials and featuring reduced number of moving parts and direct control schemes, elements which are essential for many application areas requiring fast design, real-time control and high performance. The approach consists into presenting the design, modeling, development, characterization and finally control of a series of actuators capable of linear or angular stroke. The main advantage of the proposed design approach resides in its modularity, allowing a rapid development in diverse dimensions according to the specified performances. For that, the design is emphasized on the conversion principle of the shape memory effect in the useful mechanical work, specific calculations for the mechanic and electronic subsystems, the operation and the integration of the electronic module in the mechanical structure. Afterwards, the characterization of the actuators is detailed. Finally, a closed-loop controller scheme is proposed for the actuators, using an original dual-input-single-output controller in order to improve both response time and linearity. The closed-loop experiments were performed on the linear actuators and demonstrate the efficiency of the proposed scheme.

Keywords: actuator, shape memory alloy, rotary, linear, modular, control

1. INTRODUCTION

High-performance mechatronic systems require new and improved actuation systems. Size reduction, an important trend in today's technology, implies use of new types of actuators whose actuation effect is achievable by induced strain of active elements made of *smart* or *intelligent* materials. These materials have some properties that could be in a significant extent changed in a predictable, controlled and useful manner by different external stimuli: temperature, stress, pH, moisture, electric field, magnetic field (Wadhawan, 2005). Their characteristics allow design of simple, space-efficient, low-weight and reliable actuators (Fumagalli et al., 2008). Among other such advanced functional materials which have recently been developed there are SMA, the Shape Memory Alloys, having attractive features as actuators or actuation elements.

As it is known (Duering et al., 1990), the effect of shape memory is the property to recover the previous size or the previous shape when incur a procedure of heating. Alloys with shape memory can be at low temperatures deformed plastically and after that to be able to return on the previous shape. If the shape memory recovery produces a motion against a stress, a mechanical work is done and the SMA element takes the role of an actuator.

The advantages of SMA actuators are: small size, large range of displacement, light weight, low complexity, smooth operation and reliability. On the other hand, their slow cooling, reduced energy efficiency and the nonlinear properties are some major drawbacks (Mandru et al., 2007, 2008a). The achieved performances are consistent with the ambient temperature and depend on the strain levels and the heat conduction.

The alloys with shape memory require difficult techniques of processing, thus only very simple SMA structures are often found in existing actuators. Besides helical springs, ribbons, strips, diaphragms, tubes, SMA wires in different sizes equip the actuators of this type. The SMA wires can be stretched when below the transition temperature and reversely, when heated until the necessary level for transformation temperature, they will recover their original shorter length and will be reduced with an amount of up to 5 percent of the initial dimension, developing tensile force, proportional to the diameter of the wires (Glibertson, 1994). The SMA wires may be heated by Joule effect, i.e. passing an electrical current through them.

Many actuators based on SMA wires were investigated and implemented. (Dunlop and Garcia, 2002) proposed a binary actuated Stewart small size platform. It uses NiTi wire actuators, switched on and off to control the position. The SMA wire is pre-tensioned using a bow. The mechanical design is based on compliant joints actuated by SMA wires. The electrical resistance of the NiTi wire is used to determine the operating temperature and the strain. (Scott, 2005) developed a SMA actuated control valve. An electrically heated SMA wire is mechanically coupled to a mechanism which opens and closes the valve. (Zhong and Chan, 2007) studied the performance of a gripping device which is closed by the contraction of a SMA wire and opened by a torsion spring. The influence of SMA wire diameter, torsion spring torque and driving current on gripping force, response time and cyclic test number were detailed. (Sreekkumar et al., 2007) reviewed other current successful applications of SMA wire actuators in the field of intelligent robots and devices, common to both medical and non-medical areas. The SMA actuators are applied in minimal invasive surgery, underwater robots, artificial limbs, self-reconfigurable robots, walking and in-pipe mini-robots. (Lake, 2009) proposed a safety valve actuated by a SMA wire engaged with a pulley system. One end of the wire is fixed, while other is connected with a movable element with linear displacement against a bias helical spring. (Takahashi, 2009) described linear actuator made of a hollow element through which a SMA wire was inserted. The bias spring exhibits stable performance and the SMA wire was electrically insulated from the bias spring.

One of the limitations of the above-presented actuating systems concerns their limited effective strain, acting directly, without an amplification structure. Also, the reduced blocking force makes them not suitable for those applications in which large force must be exerted.

There were several attempts to develop improved SMA actuators in compact designs, with amplified force and/or stroke. (Campanile et al., 2004) described a fish mouth-like an actuator using the interaction of a material with shape memory (a bundle of NiTi wires) together with a mechanism flexible, in order to amplify the actuator's stroke. (Mernoe, 2005) has proposed a compact linear actuator with two SMA wires in antagonist configuration arranged for a rotation and a mechanical transmission which converts rotation into linear movement of the output element. An original design of the actuator with multiple SMA wires, in a bundle structure, has been presented by (Kratz et al., 2006). It combines single SMA wires as in a biologically inspired muscle. The actuator is scalable in force and length and offers the possibility of arranging the fixings in any direction. (Selden et al., 2006) have developed a new approach to the design of SMA wire actuators: the SMA wire is segmented into many segments individually controlled. According to this new method, the binary state of individual segments is controlled; in this way, the movement is directly proportional to the total size of the sections heated. (Elwaleed et al., 2007) have studied the amplification of the displacement of a SMA wire which is fixed eccentrically along a flexible beam. The developed linear actuator consisted of two such beams, fixed to one moving and another fixed plates. (Kode and Cavasoglu, 2007) have proposed a hybrid actuation system to the end-effector of a laparoscopic instrument. It combines a DC micro-motor and a SMA actuator in series. The SMA actuator consists of multiple SMA wires assembled mechanically in parallel. A new rotary servo device has been presented by (Song, 2007). It uses a SMA wire wound on a threaded non-conductive rotor. Since one end of the wire is fixed to the rotor and the other end is fixed to the supporting base plate and provided that the rotor is connected to a pre-tensioned torsional spring, a two-way rotation can be achieved. (Lan et al., 2009) have shown that combining SMA as driver and flexure as load transmitter makes them suitable for high precision and compact space tasks. Rotary systems using a single SMA wire actuating three symmetrically identical arms of the monolithic flexures were studied and a controller was implemented to precisely control the output motion. (Romano and Tannuri, 2009) have studied a rotary actuator containing a SMA wire attached to a pulley. A forced cooling system based on thermoelectric Peltier effect provided the advantages of a reduced weight and a simpler control strategy as compared to other cooling systems.

Our past efforts (Lungu et al., 2008, 2010; Mandru et al., 2008a) have been focused to realise some new systems with actuators, in the fields of the mini and micro robotics (mini grippers, mobile wheeled systems and in-pipe mini-robots, connection mechanism for self-reconfigurable robotic systems) and the rehabilitation solutions engineering like tactile display, multi-actuator for artificial muscles, dexterous hands, upper limb prosthesis or new linear and rotational actuators were also the subject of the investigations (Mandru et al., 2008b).

To date, the research on different shape memory materials is extensive. The study of CuZnAl, CuAlNi and Nickel-Titanium (NiTi) opens new perspectives on actuators development. NiTi alloy is the most suitable SMA in case of solutions that require controllability or high activity on unit volume or a large number of replays, biocompatibility and low energy for initiations (Huang, 2002, Fumagalli et al., 2008).

In this paper, new family of linear and rotary SMA actuators is introduced. Based on a modularity approach, different sizes (for different input and output parameters), a compact design (the main active components, the structure of the mechanism but also the supervising system placed inside a casing) - with facile connection with the mechanisms of the actuators or energy supplying sources – are possible. This category of silent and miniaturized actuators, which do not require lubricants, with a reduced moving elements could be used for different specialised applications in the field.

The paper is organized as follows. Section-2 reminds the modular design used for the development of the SMA actuators. Section-3 and section-4 are dedicated to detail the development of the linear and rotary actuators respectively.

The characterization of the actuators is afterwards presented and finally, a control design is proposed in order to enhance the performances such as accuracy and response-time. The section-5 presents some experimental results on its characterization and control.

2. MODULAR DESIGN OF THE SMA ACTUATORS

In order to accomplish the above mentioned tasks, the module-level family design is an adequate approach. To achieve SMA actuators can be use a modular system considering the components that perform the same function. These modules can be interchangeable between them, in this way can be developed several types of actuators. The development of SMA actuators in a modular system facilitates diversification and increasing complexity, having several advantages such as the efficiency of organising the processes and the complexity of the design, the quickly reconfiguration and easy control and maintenance, parallel development of components, more variants for the customer's, easy assembly and flexibility in component reuse (Jose and Tollenaere, 2005, Wang, 2005).

Based on the functional decomposition approach (Asan et al., 2004; Zhang et al., 2006), the general function of the SMA actuators (conversion of electrical input energy in useful output mechanical work) is decomposed in elementary functions. A modular structure of SMA actuators is shown in Fig. 1 (Mandru et al., 2009b).

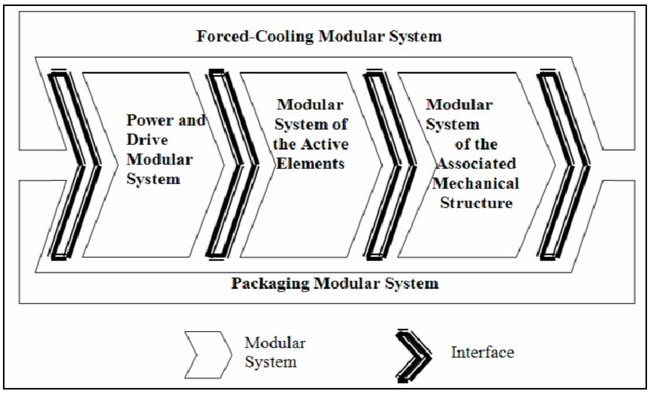


Fig. 1. The modular structure of the SMA actuators.

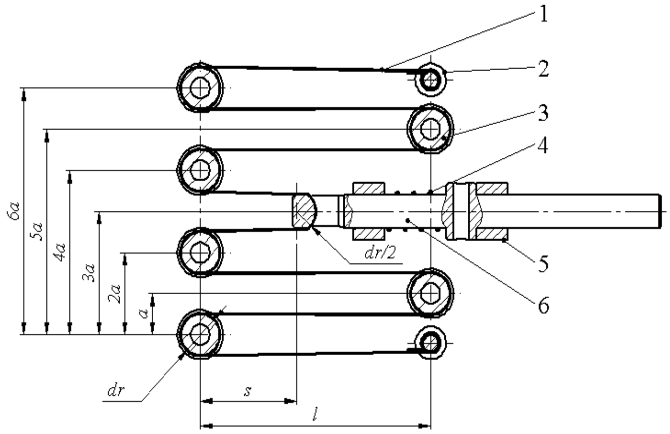
Applying the modular design method, the SMA actuators are derived from a common platform but achieve different output parameters.

3. DESIGN OF THE SMA LINEAR ACTUATORS

The linear actuators were designed in a compact way to serve a broad range of applications, such a pulley mechanism that fits SMA wire(s) into the casing. A bias spring is provided to preload the wire(s) and to elongate the wires upon the contraction of the shape memory. The both wire(s) ends are linked to the housing (Fig. 2). By heating using the Joule effect, the wires contract and act to the output component, pulling them.

According to Fig. 2, the main shaft 6 is guided by the bush 5. The SMA wire 1 is guided by the rollers 3 to ensure a greater length of the wire and therefore a larger displacement of the actuator's output element.

The wire's guide rollers are made of thermal and electrical insulation material. The fixing elements 2 are covered with a plastic protective tube.



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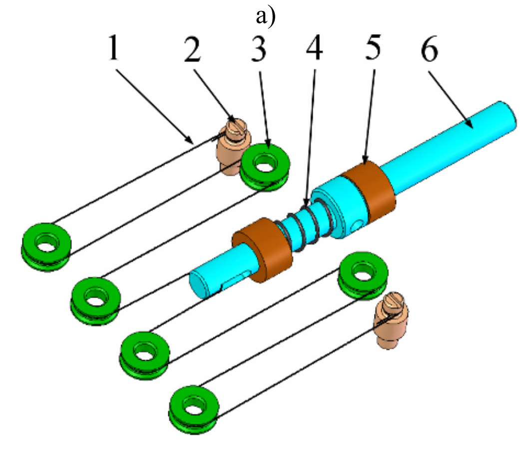


b)

Fig. 2. The mechanical structure of the linear actuators.

Three types of linear actuators are proposed, named as MAMF-01-00, MAMF-021-00 and MAMF-03-00.

Table 1 contains the relative construction values to each actuator (l is the distance between the fixing element 2 and roller 3, s is the initial distance between the rollers and the drive shaft, a is the distance between rollers, d_r is the rollers diameter and d_f is the wires diameter).

Table 2 illustrates the functional parameters of the linear SMA actuators. The force values differ, depending on the diameter of the SMA wires. F_d is the deformation or bias force which is exerted by the helical spring.

All linear actuators documented in Table 2 are equipped with a single wire. A more diverse set of values can be obtained by connecting the SMA wires mechanically in parallel.

The strokes of the three actuator sizes are 3.9 mm, 5.7 mm and 8.1 mm.

Table 1. The constructive characteristics of the linear actuators.

Assembly	l [mm]	s [mm]	a [mm]	d_r [mm]	d_f [µm]	σ_a [MPa]	σ_{amax} [MPa]
MAMF-01-00	30	12.5	5	5	25,37…375	190	600
MAMF-02-00	50	12.5					
MAMF-03-00	70	32.5					

Table 2. The functional parameters of the linear actuators.

Valid for all					MAMF-01-00		MAMF-02-00		MAMF-03-00	
No.	d_f [mm]	F_{ef} [N]	F_{max} [N]	F_d [N]	l_t [mm]	f [mm]	l_t [mm]	f [mm]	l_t [mm]	f [mm]
1	0.025	0.09	0.29	0.034	260	3.90	380	5.70	540	8.10
2	0.037	0.20	0.64	0.075						
3	0.050	0.37	1.18	0.137						
4	0.075	0.84	2.65	0.309						
5	0.100	1.49	4.71	0.550						
6	0.125	2.33	7.36	0.859						
7	0.150	3.36	10.60	1.236						
8	0.200	5.97	18.84	2.198						
9	0.250	9.32	29.44	3.434						
10	0.300	13.42	42.39	4.946						
11	0.375	20.97	66.23	7.727						

The total length of the SMA wire l_f is given by Eq. (1).

$$l_t = 6l + 7 \cdot \frac{\pi \cdot d_r}{2} + 2s \quad (1)$$

Knowing the total length of wire one can obtain contraction and displacement of the drive shaft, using Eq. (2).

$$f = 0.03...0.05 \cdot \frac{l_t}{2} \quad (2)$$

The effective and the maximum forces developed by the actuators can be determinate with Eqs. (3) and (4):

$$F_{ef} = 2\frac{\pi \cdot d_f^2}{4} \cdot \sigma_a \quad (3)$$

$$F_{\max} = 2\frac{\pi \cdot d_f^2}{4} \cdot \sigma_{a\max} \quad (4)$$

where σ_a and $\sigma_{a\max}$ are the recommended and maximum tensile stresses of the SMA material.

The elongation of the SMA wire after the shape memory contraction is provided by a helical spring. The helical spring is sized according to the corresponding diameters of the SMA wires.

A 3D model of a linear actuator is given in Fig. 3a. The elements within the structure are numbered. In Fig. 3b, the three linear actuators and their overall dimensions are detailed.

The electrical parameters of the actuators were analysed taking into account the resistive heating of the SMA wires.

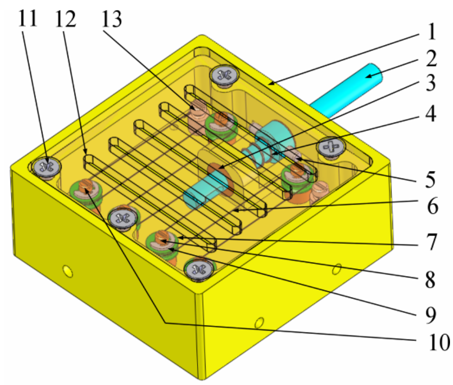


Fig. 3a. 3D model a linear actuators.

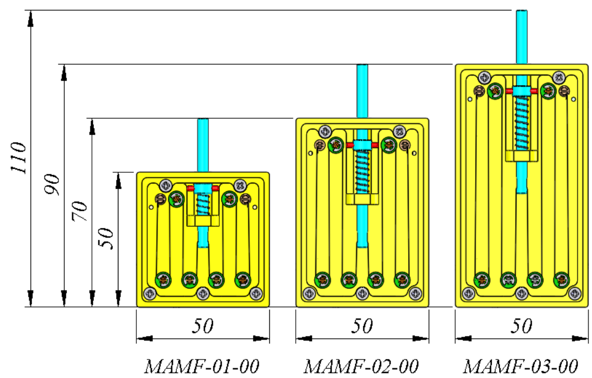


Fig. 3b. The three linear actuators and their overall dimensions.

The electrical resistance of the SMA wires R_{amf} is given by Eq. 5, where R_c is the linear resistance, usually given in Ω/m.

$$R_{amf} = \frac{R_c[\Omega/m] \cdot l_t[mm]}{1000} \tag{5}$$

The SMA wires are actuated using a Darlington bipolar transistor in a common emitter amplifier configuration. The value of voltage U_{al}, the current collector I_c, the collector emitter voltage U_{CE} and electrical resistance of the wire R_{amf} being known, the current limiting resistance R_1 is given by:

$$R_1 = \frac{U_{al} - U_{CE} - I_c \cdot R_{amf}}{I_c} \tag{6}$$

The effective current passing through the SMA wire and the dissipated power can be determined by Eqs (7) and (8).

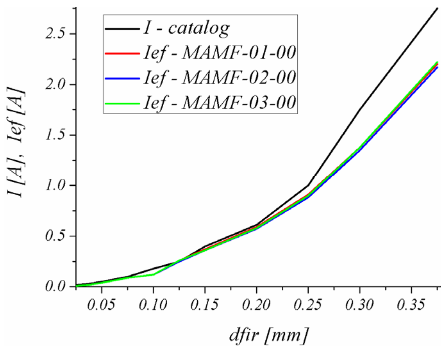
$$I_{ef} = \frac{U_{al} - U_{CE}}{R_1 + R_{amf}} \tag{7}$$

$$P_{R1} = R_1 \cdot I_{ef}^2 \tag{8}$$

The resistance R_2 is determined according to the control voltage U_c:

$$U_c = I_B \cdot R_2 + U_{BE} \Rightarrow R_2 = \frac{U_c - U_{BE}}{I_B} \tag{9}$$

By using the above presented relations, the electrical parameters are calculated. The use of low voltage values reduces the dissipated power and leads to the elimination of limiting resistance.



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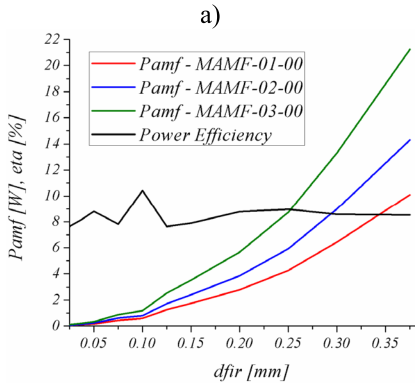


b)

Fig. 4. The load current and the power dissipation on different SMA wires diameters.

For given voltage values, there is an exponential increase of the dissipated power with the SMA wire diameter, according to Fig. 4a and Fig. 4b, where the variations of currents and dissipated power are plotted.

An electronic circuit was used to supply the linear actuator as in Fig. 5. An ATmega8 AVR microcontroller controls the PWM applied to the SMA wire by the means of a Darlington transistor Q1 TIP122. The SMA wire is connected to the PCB connector J3. The current passing through the wire is measured via the resistance R7. The corresponding voltage drop is increased by the amplifier U2 µA741, mounted in a differential amplifier circuit. The amplified voltage U2 is finally applied to the analog-to-digital (ADC) channel of the microcontroller at the pin PC02 (ADC02).

The measured current serves as a feedback signal to the actuator control algorithm. Simultaneously, the control algorithm includes the displacement measurement performed by a potentiometer, which is connected to the cable connector J1. The electrical signal from the potentiometer is applied to the microcontroller pin PC04 (ADC04). The electronic diagram is designed to be controlled by either an analogical input (PC05-ADC05) or a digital input (Rxd, Txd). The signal type switch is done through the resistors R2 and R5 which are used as jumpers. The control algorithm is designed for a 5V analogue output, providing 5mm actuator displacement. The circuit reference signals are applied through connector J2. The microcontroller operates at a frequency of 8MHz and can be programmed using a standard STK200 programmer.

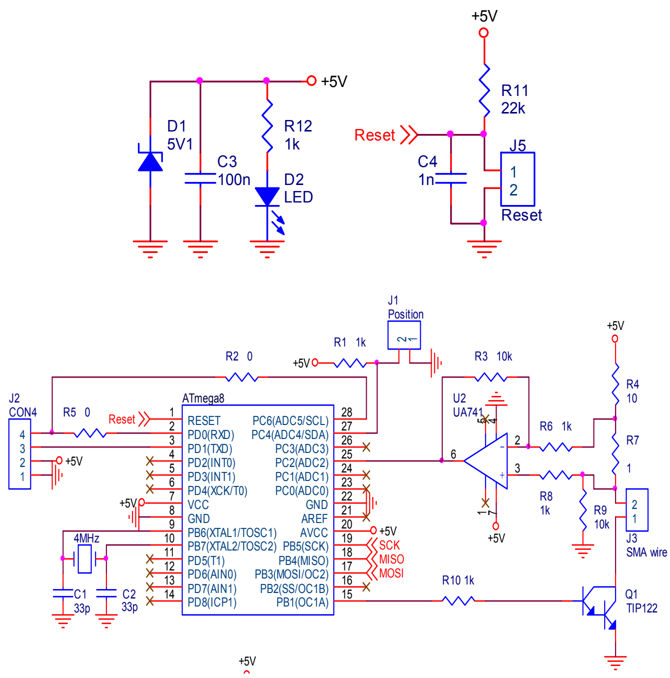


Fig. 5. The electronic schematic of the linear actuator.

The electronic layout is mainly designed with SMD components. For a proper fitting of the wiring and of the housing, the electronic circuits were exported to Solidworks Circuits. An integrated electro-mechanical design format .IDF (the Intermediate Data Format) was used to make the transfer. Once imported inside Solidworks Circuits, the 3D wiring board was created and the electronic components were imported from the software/online library.

4. DESIGN OF THE SMA ROTARY ACTUATORS

The rotary SMA actuators have a mechanical structure similar to the linear actuators presented above. The principle of functioning of one rotary actuator is depicted in Fig. 6a and Fig. 6b. The operating principle is based on the winding of two SMA wires 3 on the drive roller 2 which is connected to the spindle 1 of the actuator by a pin 4. The SMA wires are guided by the rollers 9 and fixed by the elements 11.

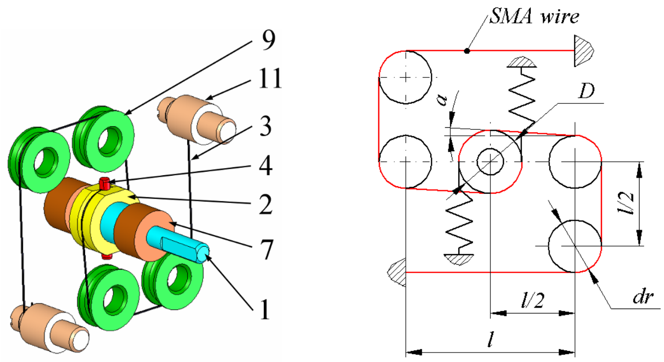


Fig. 6. The operation principle of the rotary SMA actuators.

The calculation of the SMA wire dimensions was based on the structural scheme displayed in Fig. 6b. We developed three types of actuators with different values of the geometric parameter l (16mm, 32mm and 48mm). The total length of the SMA wire has been therefore derived with Eq. (10) and the wire strain by using the Eq. (2).

$$l_t = 2l + \frac{\pi \cdot d_r}{2} + \frac{\pi \cdot D}{4} \tag{10}$$

where d_r is the diameter of the guiding rollers and D is the diameter of the driving wheel. The distance between the roller and the roller drive was considered $l/2$, approximating that the difference between the two rolls diameters is much smaller than the distance between their centres.

The angular displacement of the shaft can be calculated with Eq. (11) and the recommended torque and the maximum torque with Eqs. (12) and (13).

$$\theta = 2\frac{f}{D} \cdot \frac{180}{\pi} \tag{11}$$

$$M = F_{ef}\frac{D}{2} = \frac{\pi \cdot d_{fir}^2}{4} \cdot \sigma_a \cdot \frac{D}{2} \tag{12}$$

$$M_{\max} = F_{\max}\frac{D}{2} = \frac{\pi \cdot d_{fir}^2}{4} \cdot \sigma_{\max} \cdot \frac{D}{2} \tag{13}$$

Based on these relations, we derive the constructive and functional parameters of the rotary actuators. Fig. 7a shows the variation of the recommended torque and the maximum torque for different diameters of the SMA wire.

The model of rotary actuator was designed (MAMF-04-00, MAMF-05-00 and MAMF-06-00), as illustrated in Fig. 7b.

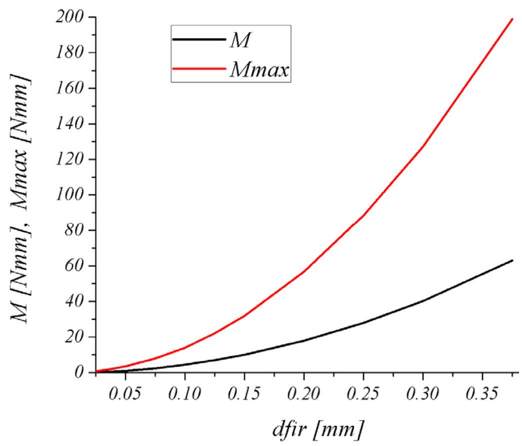


Fig. 7a. The variation of the torque depending on the SMA wire diameter.

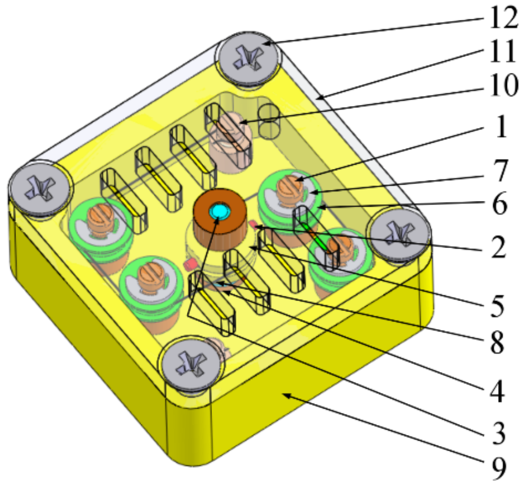


Fig. 7b. 3D mechanical model of the designed rotary SMA actuator.

An electronic circuit similar to the one used for the linear actuators was designed for the rotary actuators. The electronic diagram is composed of an ATmega8 microcontroller. The SMA wire is actuated through PWM pulses with a TIP127 Darlington transistor. The scheme also includes electronic current sensors and position sensors, a microcontroller programming circuit, power circuit and the external oscillator.

The main difference with respect to the linear actuators circuit is that a number of two wires are successively actuated. The wires are connected via the connectors J3 and J4 in the emitters of the Q1 and Q2 transistors respectively.

Based on the above presented working principles and formulae, we manufactured and assembled several prototypes as the ones shown in the Fig. 8. A reason for using aluminium housing is to allow a good cooling of SMA wires and also to be easily integrated into industrial processes. In Annex I and II can be found more details regarding linear and rotary actuators.

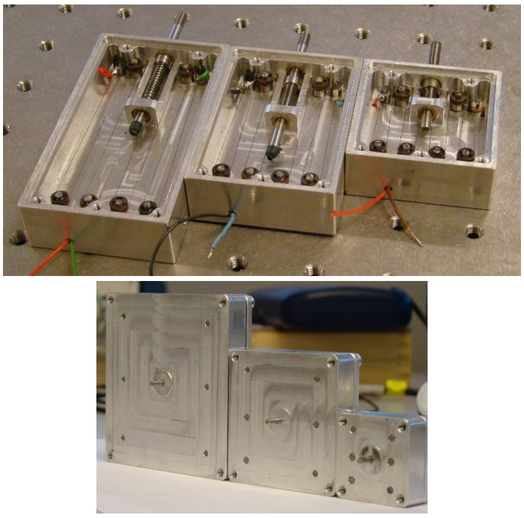
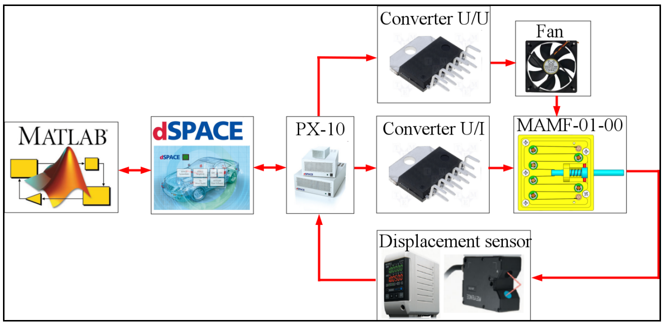


Fig. 8. Pictures representing the developed prototypes of linear and rotary SMA actuators.

5. THE TEST BENCH FOR THE SMA ACTUATORS

The specific measurement principle of the developed test bench is shown in Fig. 9a. It is composed of three main parts: the software program (under Matlab-Simulink environment with the ControlDesk interface), the electronic part (a DSpace board, a voltage-to-current converter and a voltage-to-voltage converter with high output current capability), an optical linear sensor (LK-G125 from Keyence) which provides 10nm of resolution and 500nm of accuracy, and the mechanical part (consisting of the developed SMA linear actuators).



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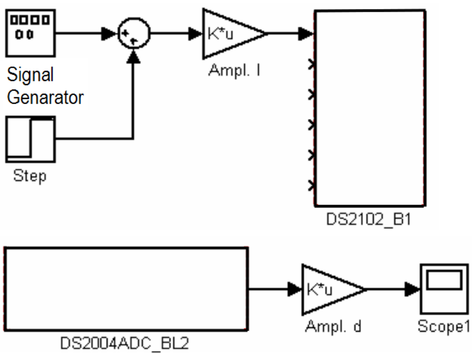


b)

Fig. 9. a) The block diagram of the linear actuators testing workbench. b) Simulink model.

Matlab-Simulink environment is used to acquire the measurement from the optical sensor but also to generate input signals (ramp, step, sine and pulse, (Fig. 9b).

The generated signal is afterwards amplified by a voltage to current amplifier and converter in order to supply the SMA actuators. The voltage to current converter is based on a power op-amp OP541 that, if supplied with proper hear sinks, may supply up to 5A, which is largely sufficient in our case. Finally, the ControlDesk software which is linked with Matlab and the DSpace board allows the real-time data acquisition and control. The sampling time is set equal to 10ms. In Fig. 10 can be observed a linear actuator cooled by using a fan. This photo was made at the testing manoeuvres.

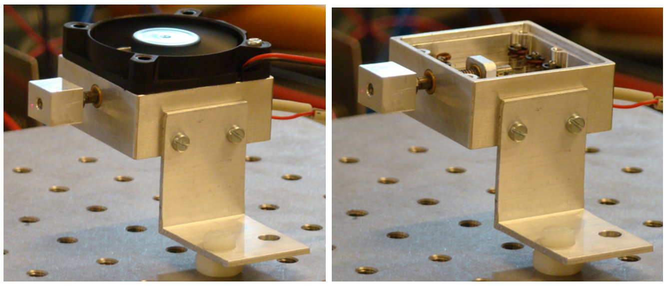
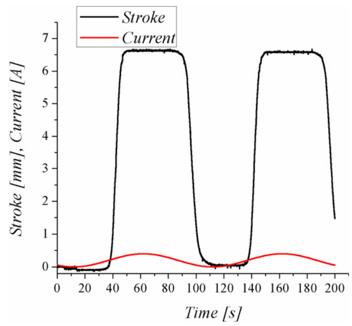


Fig. 10. SMA linear actuator with and without fan cooling.

5.1 Testing the linear actuator without control

The measurements start with the characterization of the mechanical system. The results here can be further used to design an adequate closed-loop control. Identification signals are sinus waveforms at 0.01Hz, 0.05 Hz and 0.5 Hz frequency. Fig. 11 and Fig. 12 present the obtained results of the MAMF-03-00 actuator, with a 150µm diameter of the SMA wire.



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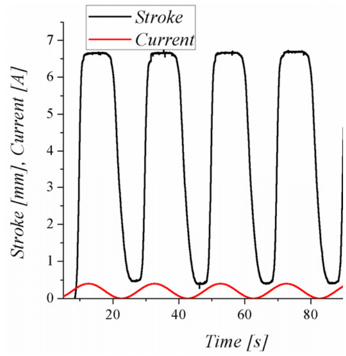

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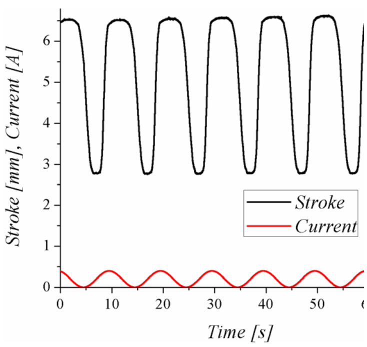
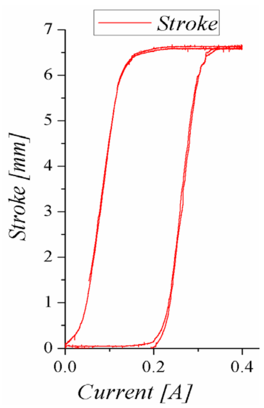
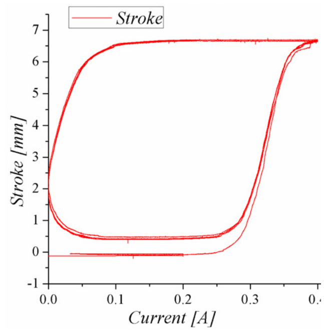


c)

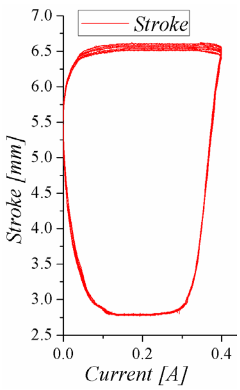
Fig. 11. Applied current and related displacement output variation of the MAMF-03-00 actuator of 150μm diameter, for a sine wave of frequency 0.01Hz(a), 0.05Hz(b), 0.5Hz(c).



a)



b)



c)

Fig. 12. Current - displacement characteristics of the MAMF-03-00 actuator, for a sine signal at 0.01Hz (a), 0.05Hz (b), 0.5Hz (c) frequency and 150μm diameter of the SMA wire.

By analyzing these graphs, one can notice a rather good behavior of the actuator for low frequencies, up to 0.1Hz, as seen in Fig. 11. As expected, the apparent hysteresis is generated (Fig. 12) due to the shape memory effect and the slow thermal response (Fig.11). However, from certain frequencies (from 0.5 Hz frequency), the output displacement range starts to be lost, Fig. 11c). In particular, it can remark the difference during the heating process and the cooling process. The latter is much slower than the former. Under these conditions, a closed-loop control and forced cooling process must be applied. In addition to the response-time enhancement, this control will also enable the improvement of the accuracy.

5.2 Testing the linear actuator with control

The block diagram of the SMA actuator is displayed in Fig. 13a. The actuator can be considered as a single-input-single-output (SISO) system: while the control signal is the current applied to the SMA wire, the output is the displacement. In order to improve the cooling process, we embed a cooler system (based on fan with DC motor) system supplied by a voltage U on the mechanical. The system to be controlled therefore becomes a dual-input-single-output (DISO) scheme (Fig .13b).

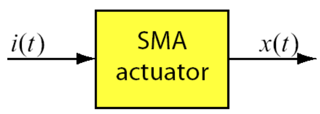


Fig. 13a. The SISO block diagrams of the SMA actuator.

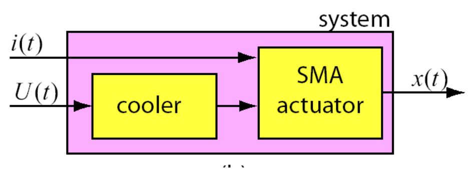


Fig. 13b. The DISO model of the SMA actuator with cooler.

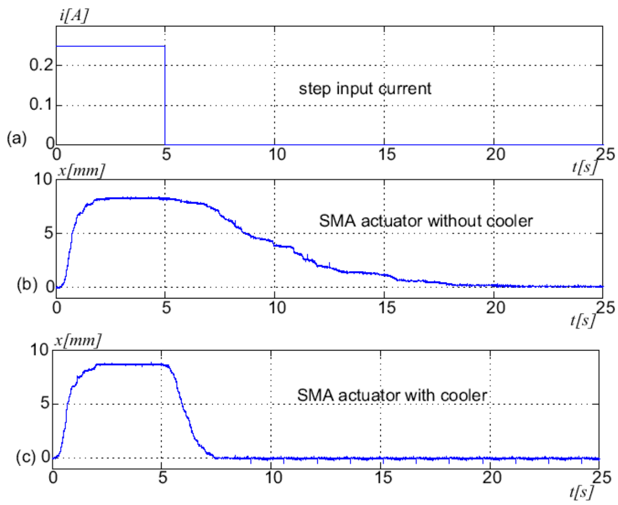


Fig. 14. (a) Step input current applied to the actuator, (b) Step response of the actuator without cooler, (c) Step response of the actuator with cooler.

Fig. 14 present the experimental responses of the actuator when a step input current i=0.2A to 0A is applied to the SMA wire. It can see that the response is clearly accelerated when using the cooler relative to that without cooler.

To control the DISO system, we use the scheme presented in Fig. 15 where a Proportional-Integral (PI) scheme is used for the SMA wire and a bang-bang for the cooler. It results:

For the PI controller:

$$i(t) = K_p \varepsilon(t) + \int_0^t K_i \varepsilon(t) dt \qquad (14)$$

For the bang-bang controller (cooling fan switch):

$$U(t) \begin{cases} = A[V] & if \quad \varepsilon(t) \geq 0 \\ = 0[V] & otherwise \end{cases} \qquad (15)$$

Where K_p and K_i are the proportional and integral gains, and A is a constant.

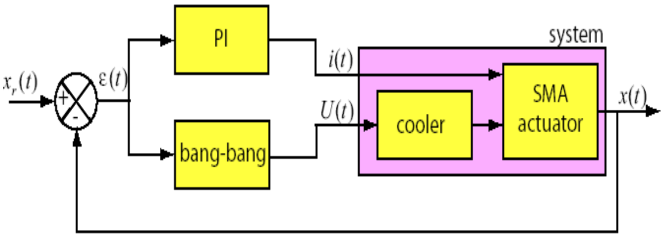


Fig. 15. The block diagram of the closed-loop control.

All the experiments were performed with and without the cooler in order to make comparisons between the results. If the cooler is used, we employ *A=8V* for the bang-bang controller. The gains of the PI controller are tuned accordingly to the Ziegler-Nichols method which provides good results for the application. We derive: Kp=0.2 and Ki=0.2. First, the tracking capability of the actuator is analyzed. For that, we apply a sine input reference to the closed-loop.

We performed more tests and analyzed the graphics results using a sine signal of 0.01Hz, 0.02Hz and 0.05Hz, tracking performances of the closed-loop for both situations, without cooler and with cooler.

Comparing the results for different values of frequency when the system is without the cooler and the temporal responses of the closed-loop when using a cooler, by still using the same sine input reference, it can see that without cooler, the tracking starts to be lost from f=0.05Hz, while this is not the case when using the cooler.

Without cooler, a hysteretic behaviour can yet appear at a frequency between 0.01Hz and 0.02Hz, but the hysteresis is well compensated when the closed-loop is with the cooler for the same frequencies, as shows the corresponding reference-displacement map.

Finally, as we can see comparing the two cases, the ascending curves (corresponding to the heating process) are quasi-similar when working with or without the cooler. During the descending curve however, corresponding to the cooling process, the response is clearly rapid when the bang-bang controller is used (i.e. with the cooler).

The results also demonstrate the accuracy when using the proposed closed-loop control scheme (static gain is null).

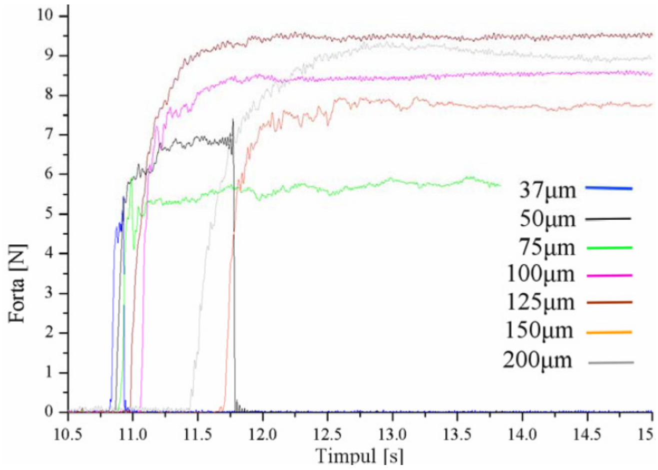


Fig. 16. The maximum force and response time to the nominal current value for different wire diameters.

The maximum force that can be developed by the actuators is 10.6N for wires with 150µm diameter according to Table 2. The actuators efficiency from the power dissipation on wires can be seen in Fig. 4.

In some measurements performed on these wires with this diameter a force of 7.8N was developed, resulting in an efficiency of approx. 73.6% (Fig.6. Such performance is of great interest for devices with precise positioning used to research the micro and nano world.

6. CONCLUSIONS

The specific features of the actuators used in mechatronics are: simple design, decreased complexity, mass, inertia and price as well as good controllability. The Shape Memory Alloys actuators can be considered as an alternative for the actuation principles and can be used for such actuators.

This paper presented the design, development, characterization and control of modular SMA actuators with simple design scheme. Both linear and rotary motions are considered in the design and development. The proposed linear actuators are designed similar to biased actuators, which are capable of moving the output element back (inside) by heating SMA wire. The rotary actuators are designed as two-way actuators which include two SMA wires.

The linear actuator is afterward characterized and a simple control scheme used to improve both the response time and the accuracy is proposed. The simplicity of their mechanical design and reduced number of moving components make the proposed actuators useful for many application areas. On the basis of the authors' previous works on shape memory alloy (SMA), other future work will include finding optimal shapes by exploring the modelling methodology presented.

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