Comparison Among Different Modular SMA Actuated Flexible Fingers

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Abstract. Four prototypes of a flexible finger, each made up of three actuator modules based on shape memory alloy (SMA) wires, are experimentally studied in this research. A module is basically composed by few simple components: a plastic body, made of different materials, and SMA wires. The bending of the module is performed with the heating and cooling of the SMA wires and the central rod exerts bias force, necessary to the stretching of the wire to the original shape. To evaluate the actuator workspace different tests were performed, and the results of three prototypes are compared. Finally a more complex prototype in which the antagonist wires can be deactivated during the working cycle was designed and preliminary tests were performed, obtaining encouraging results.

Keywords: Shape memory alloy · SMA wires · Flexible actuator
Modular actuator · Experimental test

1 Introduction

It is known that Shape Memory Alloys (SMA) are rather interesting for robotic applications [1–5], although they also have several defects that limit their diffusion at the moment. It remains interesting to continue to study new applications in which their undoubted qualities, first of all the power/weight ratio [6], but also sensing ability, remotability, low driving voltage, simplicity, cleanliness and silent actuation, can try to solve problems that are otherwise difficult to solve. Various researchers investigated on the limitation of their drawbacks, for example implementing different controls aiming to obtain stable and repeatable behavior [7–9]. In the field of unconventional actuators, various researchers have studied devices that take advantage of the properties of SMA wires, for example to make flexible actuators [10] or to create a simple and small element, which can be used as a basic element for more complex systems [11].

The idea presented in this work consists in the combination of the previous concepts: a SMA actuated flexible module, which can be variously assembled, so to allow the creation of fingers, having different shapes and characteristics in order to meet a wide range of needs. In particular, different prototypes, made of different materials, were tested in order to compare the various behaviors and choose the most promising for further investigations. Previous works presented the basic idea, a mathematical model implemented in order to correctly dimension and to design the prototypes [12] and experimental tests for the evaluation of the actuator work space and output force [13].

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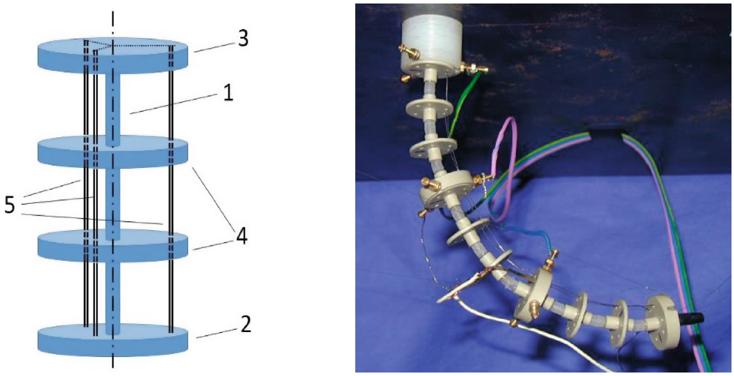
2 The Module

The modular actuator based on shape memory wires studied in this research is sketched in Fig. 1a. The represented module is composed by a central rod (1), a thin flexible cylinder with a lower (2) and upper (3) base and two intermediate disks (4). Three Nitinol (diameter 250 µm) SMA wires (5) are fixed to the lower base, cross the intermediate disks through appropriate holes, reach the upper base and then return analogously to the lower base where their other end is fixed. Suitable screws (here not represented) placed on the upper base allow the regulation of the tensioning of the SMA wires. Each wire is placed 120° from the other, in order to allow the module to bend in any direction when one or more wires are actuated. In fact, the motion of the module is performed with the heating of the wire, e.g. by means of Joule effect, which causes the shortening of the wire itself, whereas the cooling, while a bias force is applied, causes the stretching of the wire to the original shape. This bias force, necessary to the stretching of the wire to the original length is exerted in this case both by the central rod and by the inactive wires.

The modules will be joined one to the other in order to assemble fingers. As an example, Fig. 1b shows a picture of a finger made of three modules. One module length is 40 mm. Figure 2 shows the test bench for the evaluation of the actuator work space.



a) b)

Fig. 1. (a) Sketch of one module: (1) central rod, (2) lower base, (3) upper base, (4) intermediate disks, (5) 3 SMA wires @120°; (b) Prototype of a three module finger.

With reference to Fig. 2b, the heating of the wires placed in the same angular position will cause the displacement along three main directions (named 1, 2 and 3), and the simultaneous heating of the wires placed in two angular positions will cause the bending along three secondary directions (named 1-2, 2-3, 1-3).

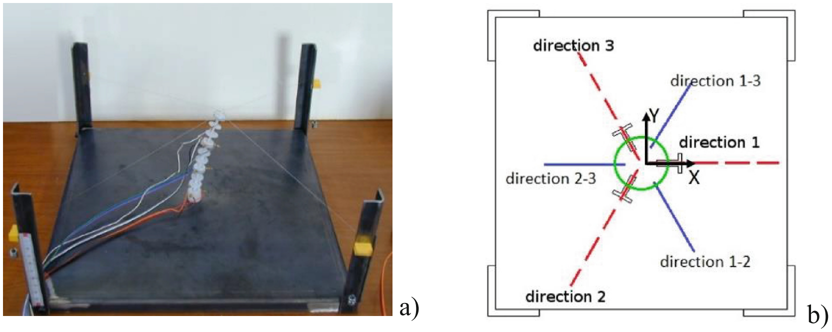


Fig. 2. (a) Picture of the test bench for the evaluation of the actuator work space; (b) View from above with actuator displacement directions

The test was carried out with step supply current of 1A for the heating phase (duration 30 s), still air for the cooling phase. Power supply is about 2.8 W. The wires activation sequence for each direction is the following: activation of the lower module, activation of the central module, activation of the higher module (near the end effector), cooling. Each sequence was repeated at least 3 times.

3 Prototypes Design

Different prototypes were designed, realized and tested. The original prototype (A) was made in nylon. It has been chosen because it has a modulus of elasticity that is not high (800–1200 MPa), so as to give to the device a good flexibility, and allows a simple machine tooling process. the result is a light, flexible and relatively inexpensive structure. Its melting temperature, around 120 °C, is however dangerously close to the temperatures reached by the wires in the hot phase, and this constitutes a point of attention. Some results of experimental testing on this prototype can be found on [13].

A second prototype (B) was then made of Teflon (PTFE), a material with excellent flexibility, but above all a high melting temperature (250 °C). A negative aspect of Teflon, instead, is represented by the difficulty in working with machine tools; in fact, it requires complex and expensive operations.

A third prototype (C) was made by alternating components made of two different materials. The bases and intermediate disks are made of a techno polymer known as PEEK 1000. This choice was dictated by the need to have elements very resistant to the thermomechanical stresses exerted by the wires high temperature. PEEK seems to offer good guarantees, thanks to the high Young's modulus (4400 MPa) and to the high melting temperature (340 °C). The only limit of this material with high performance is high cost. The flexible elements (central rod) were made using the LIM, a silicone rubber with a modulus of elasticity equal to 50 MPa.

4 Experimental Test Results

Figure 3a shows the 3D workspace obtained with prototype A, while Fig. 3b presents the 3D workspace obtained with prototype B.

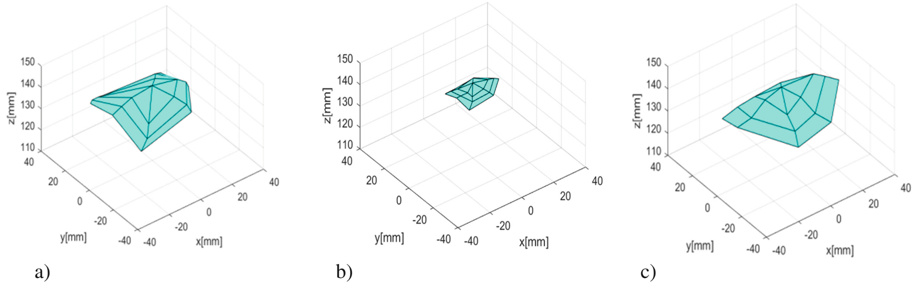


Fig. 3. (a) 3D Work space of prototype A; (b) 3D work space of prototype B; (c) 3D work space of prototype B without antagonistic wires

The nylon actuator (A) has proven to have stable and correct operation. The adopted design solutions have provided the possibility to cover large work spaces, with likely margins for improvement, further reducing the diameter of the central shaft. Lastly, the choice of nylon as a construction material proved to be good from the point of view of flexibility, but there were critical issues regarding the deterioration in areas where it is excessively heated due to the proximity to the wires. In order to continue using nylon, it will be necessary to identify design solutions able to overcome this issue, for example by adding insulating elements.

The prototype (B) is characterized by a great flexibility, but it was observed that the two non-activated antagonistic wires limit the deformation of the whole actuator. From this observation, the need arose to investigate the extent of this limitation. New tests were then performed by excluding the two pairs of antagonist wires (not activated), with the idea of comparing the two workspaces to see if it could be the case to start the project of a new prototype in which the antagonist wires could be disabled when needed. Figure 3c shows the new work-space and Fig. 4 the comparison of the two different workspaces on an xy projection.

In the third prototype (C) design, the use of new materials has given greater flexibility and, at the same time, a high thermomechanical resistance; the device, therefore, has been able to increase the working space ensuring a good strength and durability over time. A negative aspect, however, is represented by the tendency of the rubber inserts to undergo a torsion causing an irregular movement of the actuator. The same considerations made previously with regard to the antagonist wires were repeated for this actuator, tested with (results in Fig. 5a) and without (Fig. 5b) antagonist wires. In Fig. 6 the comparison is presented.

A drawback of this third prototype is represented by the difficulty of the actuator in returning to the rest configuration; this is caused by the fact that the high deformability of the central rod is paid with a too small return force.

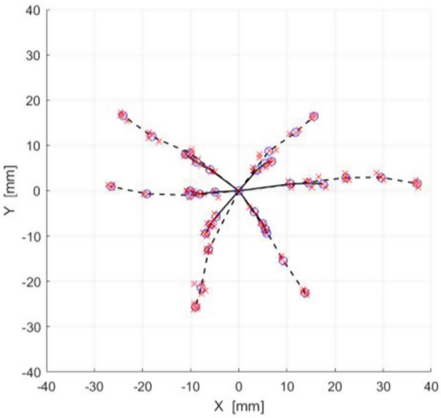


Fig. 4. XY projection of the workspaces, prototype B (cross: experimental, circle: mean values; solid line: with antagonistic wires, dotted line: without antagonistic wires)

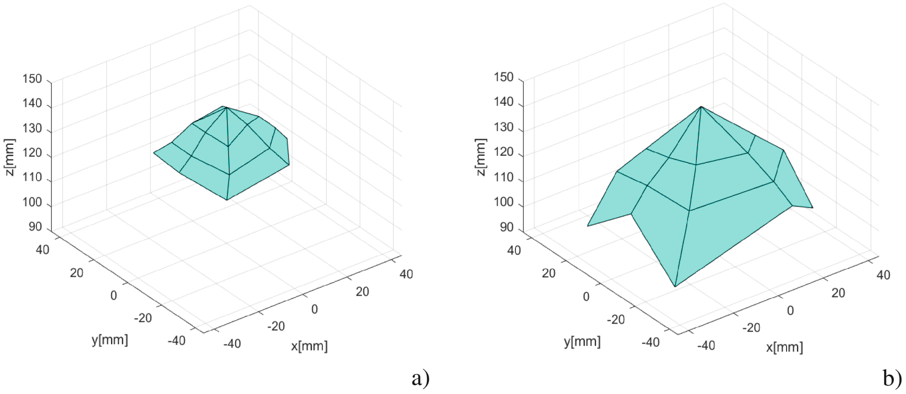


Fig. 5. 3D work space of prototype C (a) complete; (b) without antagonistic wires

5 New Prototype

Given the results of the experimental tests carried out on the three prototypes, the study focused on the resolution of the above described limits, while maintaining the goal of creating a simple and compact structure. The new main objective is then the design of an actuator in which the antagonist wires can be deactivated during the working cycle, and, at the same time, to guarantee a bias force that facilitates the return of the central rod. The price to pay will be the presence of a higher number of components, and the consequent greater dimensions.

Figure 7(a) shows the new prototype and the detail of the base in section with the activation/deactivation device, while 7(b) presents corresponding pictures. The key element that allows activation/deactivation is a cylinder (1) connected to the lower end

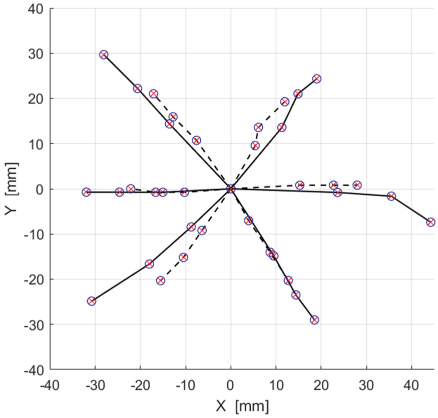
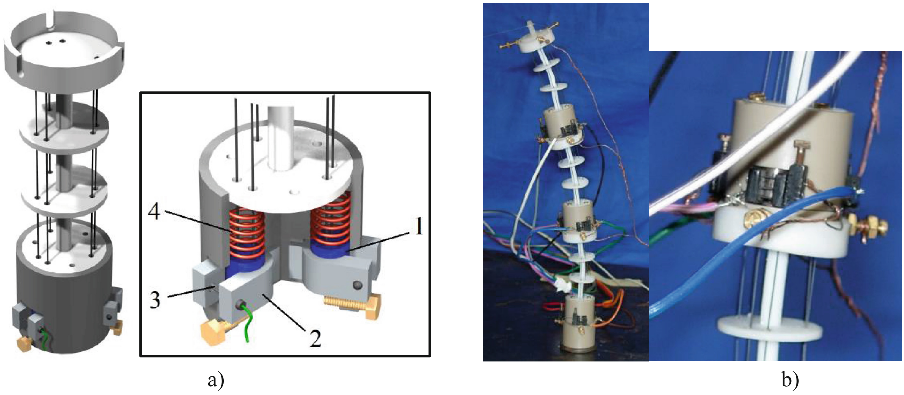


Fig. 6. XY projection of the workspaces, prototype C (cross: experimental, circle: mean values; solid line: with antagonistic wires, dotted line: without antagonistic wires)

of each wire. A shaped plastic gripper (2) wraps the cylinder and, when necessary, prevents the linear movement of the cylinder by exerting pressure on its side surface. An additional SMA wire (3) carries out the actuation of the clamp. Appropriately sized traction springs (k = 2,28 N/mm) (4) generate both the bias force for cylinders and rod and the pretensioning of the SMA wires. The module is made in Teflon (see prototype B) because, as already mentioned, it has shown to better resist the stresses, especially of a thermal nature. The new base is made of PEEK1000 and the cylinder is made of PES. The two holes for the housing of a SMA wire are arranged closer than in the previous solutions (25° instead of 40°) to allow their connection within the activation-deactivation mechanism.



a)

b)

Fig. 7. (a) New prototype and detail of activation/deactivation device on the module base; (b) picture of the prototype and detail

When a pair of wires is activated the electric current passes first through SMA wire (3) which, by operating the clamp, lock the corresponding cylinder. The cylinders corresponding to the pairs of unactivated wires are free to slide, in this way they are not exerting an antagonistic force. When the power supply is interrupted, the clamping action also stops and the cylinder is free to move again.

Figure 8 shows in black a first set of experimental results for the prototype D compared with results obtained for prototype B with antagonistic wires (in solid line) and without (in dotted line) in green. It can be observed that the work space is wider than the solution with antagonistic wires. The amplitude of the antagonist-free solution is not achieved because, obviously, sliding frictions are introduced into the solution D. It is noted that the prototype D results are not well aligned with previous tests results. This difference is due partly to the difficulty of orientating the prototype exactly with respect to the test bench, but probably also to the difficulty of obtaining exactly equal preloads on the three wires.

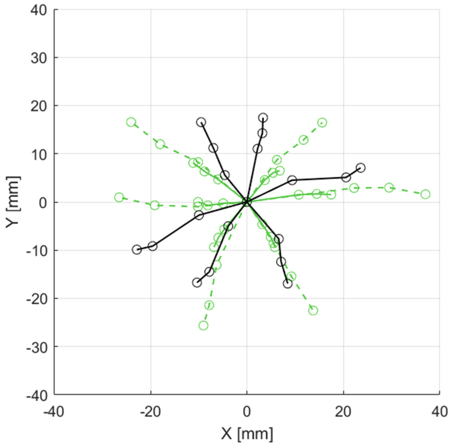


Fig. 8. XY projection of the workspace, prototype D in black, prototype B in green (solid line: with antagonistic wires, dotted line: without antagonistic wires)

6 Conclusions

Starting from the same basic idea, three different prototypes were made. The tests carried out on these devices have highlighted the advantages and weaknesses of the various design solutions. In particular, the prototype A, although having a good flexibility, has thermomechanical properties that are not sufficient to consider nylon as the right material to continue the design. The working space of prototype B is very limited, therefore it has adequate thermomechanical properties. The third solution tested (prototype C) represents an attempt to find a compromise, with heads and disks made of a PEEK1000 and silicon rubber shaft. While allowing to gain amplitude of the work space and not presenting problems related to thermal shock, this solution has shown new disadvantages: system instability and non-repeatability of the tests.

The last solution was identified thanks to the observation that a part of the antagonist force is actually exerted, not only by the central rod, but also by the inactive SMA wires included on the device. This observation led to the design and construction of a fourth prototype (D) in which a special device allows blocking or freeing such antagonist wires. The results of the tests performed on this last device are encouraging because the work-space obtained is significantly greater than that obtained by the device B, made of the same material as the device D.

The work will continue in the direction of overcoming some issues, in particular related to the component assembly and the fatigue behavior of the device. In order to avoid overheating and increase its life, a control system should be implemented.

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