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Experimental Testing of a Modular Flexible Actuator based on SMA Wires

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Abstract

A flexible finger made up of three actuator modules based on shape memory wires (SMA) is experimentally studied in this research. A module is composed by few simple components: a plastic body and SMA wires. The body is a thin cylinder with a lower and upper base and two intermediate disks. Three equidistant SMA wires are longitudinally placed and allow the module to bend in any direction when one or more wires are actuated. The motion of the module is performed with the heating and cooling of the wire and the central rod exerts bias force, necessary to the stretching of the wire to the original length.

Two test benches were built to perform both positioning tests and force tests. To evaluate the actuator workspace different tests were performed, with different power supply, heating and cooling time, actuation sequence. Force tests were performed with different distance between the undeformed finger and the obstacle.

The results achieved with this first prototype are encouraging since the finger shows stable and correct operation. The planar projection of the workspace is a circle of about 30-40 mm of radius and exerted force is similar to mathematical model results (about 1 N at 5 mm). These results are encouraging, even though, probably due to manufacturing imperfections and frictions, the movement is not very regular along the various directions.

Keywords: Shape memory alloy, SMA wires, flexible actuator, modular actuator, experimental test

INTRODUCTION

There are different kinds of grippers and different ways to categorize them. A widespread method consists of considering the different movement they perform in order to grasp the object: "traditional" grippers, parallel or angular, and "alternative grippers" or dextrous hands.

The parallel or angular grippers, having two elements facing each other and operating a parallel or angular movement, are widely used in robotics since they are simple and usually cheap [1, 2].

The dextrous hands usually have an anthropomorphous shape and the object is grasped by closing mechanical fingers. They are more versatile and they are preferred for the grasping of non-symmetric objects. Good results were obtained since the seventies [3, 4], but nowadays performances were increased with optimizations in control and gripping configuration [5, 6]. Three fingered dextrous hands are widely used and they can be assembled in different configurations.

The actuation system of the grippers can be more traditional (electrical, pneumatic) or innovative like piezo-actuation [7] or with Shape Memory Alloy (SMA) actuators [8, 9, 10].

SMA wires can also be conveniently used in gripping fingers because they are light and not bulky [10, 11], but there are also very small devices in which the structure itself of the device is made of SMA material [12, 13]. Flexible actuators are an interesting solution to use as fingers in gripping hands: actually there are different solutions, actuated by means of electric current, hydraulic fluid pressure, or pneumatic pressure [14, 15, 16].

Shape memory elements, actuated by Joule effect, can be used to cause the motion of the finger by exploiting the flexion principles of the finger structure itself. Thanks to their advantages, such as high power/weight ratio [17], sensing ability, remotability and others, many researchers investigated on devices with SMA actuators in various fields of engineering [18-25]. Moreover different controls were implemented in order to overcome their drawbacks and obtain stable and repeatable behaviour [26, 27, 9].

In this paper experimental tests on a flexible modular actuator are presented. A prototype of the flexible finger, previously designed and modelled [28], is composed by a number of simple actuator modules assembled in series in order to obtain a versatile device. Each module will consist of a flexible central beam and three wires externally arranged at 120°. The actuation of one or more SMA wires will generate the deflection of the beam in the corresponding direction. The wires are not embedded in the structure so to have a fast cooling. One gripper hand will be composed by a number of fingers depending on the task. A rigid support will constitute the base on which the electric power cables, switches and drives for the control of the structure are arranged.

The experimental tests here presented take into account the fact that, in the mechanical field, the actuator will be used as a finger for gripping hands or positioner. In the first case, it is important to investigate on the forces exerted by the device, while in the second case greater importance must be given to the precision of movement, the working space and the controllability of the structure.

PROTOTYPE REALIZATION

The modular actuator based on shape memory wires studied in this research is presented in figure 1. The module is composed by a plastic body (1), a thin cylinder with a lower and upper base and two intermediate disks, and three SMA wires (3) longitudinally placed. The wires are fixed to the lower base, pass through the intermediate discs through appropriate holes, reach the upper base and then return analogously to the lower base where their other end is fixed. Suitable screws (2) 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.

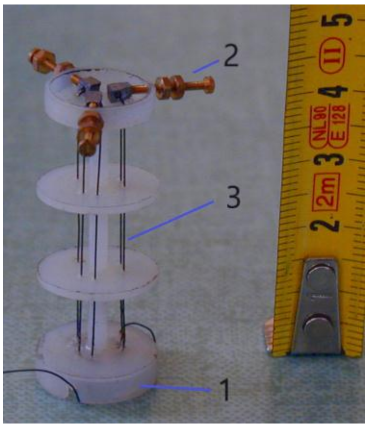


Figure 1: module: 1) plastic body , 2) tensioning screws , 3) SMA wires

A mathematical model was implemented in order to correctly dimension and to design the prototype [28]. The modules will be joined one to the other in order to assemble fingers. Figure 2 shows a picture of a finger made of three modules.

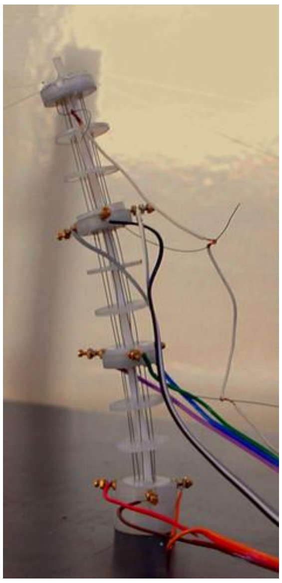


Figure 2: Prototype of a three module finger

EXPERIMENTAL TESTS

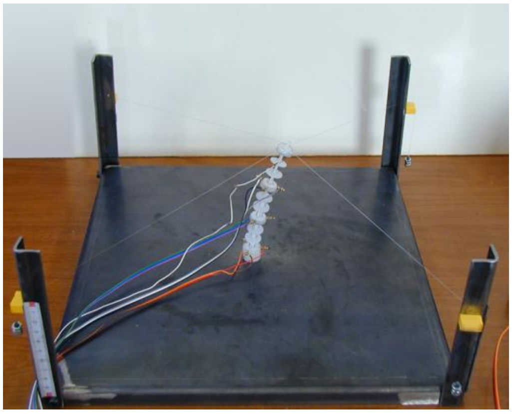
Preliminary experimental tests were carried out in order to examine the correct functioning of the actuator.

Two test benches were built to perform both positioning tests and force tests. To evaluate the actuator work space different tests were performed, with different power supply, heating and cooling time, actuation sequence. Force tests were performed with different distance between the undeformed finger and the obstacle.

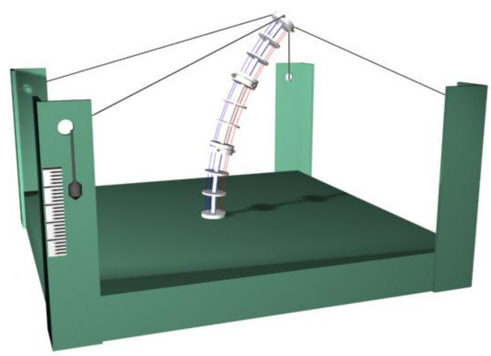
Positioning tests

Test bench

The first experimental set up, sketched in figure 3, is composed by a flat square plate with four vertical rods at its edges. The plate side length is 350 mm and the rods, having an “L” cross section, are 120 mm high. In the middle of the plate there is the clamping device for the actuator to be tested. Four low-friction nylon wires (diameter 20μm) are equidistantially fixed to the actuator top. The opposite end of each wire is inserted in a hole at the top of the respective edge rod and a little mass is suspended, having the only function to tighten the wire itself. The four wire end positions, measured thanks to rulers fixed on the vertical rods, are used to calculate the actuator end position in space by simple algebraic and trigonometric calculations.



(a)



(b)

Figure 3: Picture (a) and sketch (b) of the test bench

The test aims to evaluate the actuator displacement during different heating and cooling sequences. In particular, with reference to figure 4, the heating of the wires placed in the same angular position will theoretically 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 theoretical bending along three secondary directions (named 1-2, 2-3, 1-3).

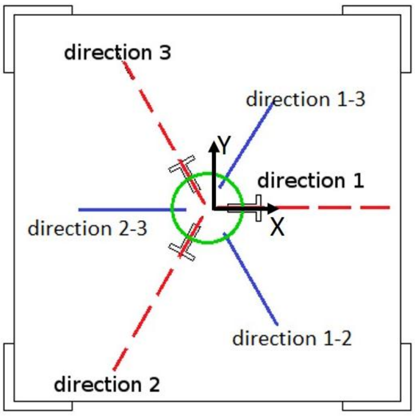


Figure 4: View from above of the displacement test bench: actuator displacement directions

Test procedure and results

The first test was carried out with step supply current of 1A for the heating phase (duration 60 s), still air for the cooling phase. Power supply is 2.8 W.

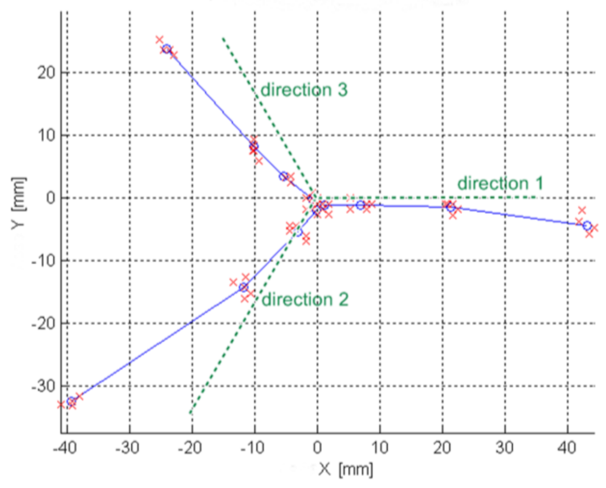
The wires activation sequence is:

- direction 1: activation of the higher module (near the end effector), activation of the central module, activation of the lower module, cooling;
- direction 2: activation of the higher module (near the end effector), activation of the central module, activation of the lower module, cooling;
- direction 3: activation of the higher module (near the end effector), activation of the central module, activation of the lower module, cooling.

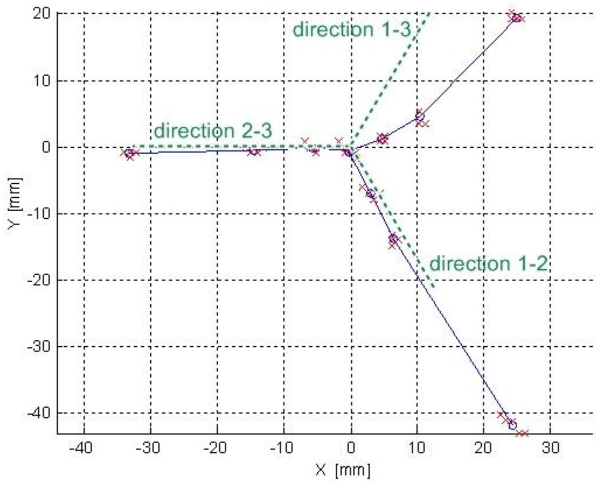
This sequence was repeated 5 times.

A second test aimed to the evaluation of the actuator displacement along the three secondary directions. The same heating/cooling sequence was then applied to couples of wires.

Figure 5 shows an example of the results of a first type (a) and second type (b) positioning test. The (red) crosses represent the positions of the upper end of the actuator on a XY plane during the heating/cooling sequence. The (blue) circles are the mean values. In green dashed lines the theoretical directions are plotted.



(a)



(b)

Figure 5: a) First positioning test, main directions; b) Second positioning test, secondary directions

It can be observed that the experimental three directions are not superimposed to the theoretical ones: this can be justified with the non-perfect symmetry of the wires on the actuator modules. Moreover the movement amplitude along the three main directions is unequal because the wire tensioning is difficult to set. However the standard deviation values, less than 3 mm, demonstrate a good repeatability.

Joining together the results of the two previously described positioning tests it is possible to draw the actuator workspace. In particular figure 6 shows a XY projection, easy to interpret.

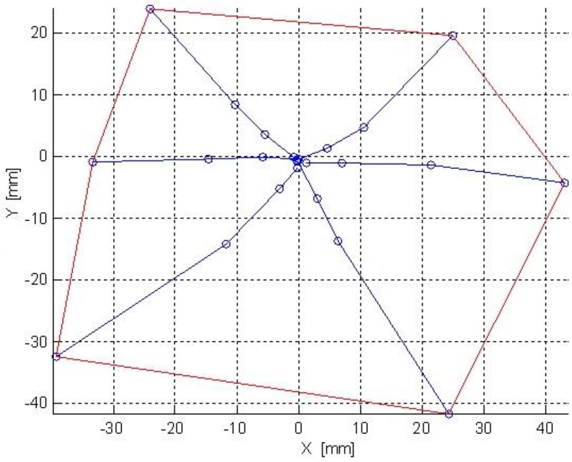


Figure 6: XY plane projection of the actuator workspace

A third test was performed in order to investigate the influence on the workspace of the modules supply order. With the same current supply and same duration the sequence was flipped to: supply of the module near the basement, then the middle one and finally the module near the end-effector.

Figure 7 shows the comparison between the first and third test. It can be observed that the total displacement differs from first test to third test, in particular in the latter a lower displacement was obtained. This probably happens because in this test the lower module is activated first, so it is in cooling phase during the activation of middle and high module, this generates a bias force for them.

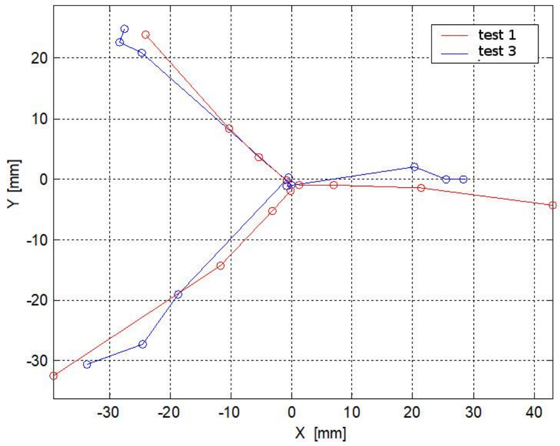


Figure 7: Comparison between first and third test: different activation modules sequence

Fourth test consisted in comparing the results with different power supply. A current equal to 0.8 A (power supply about 2.2 W) is not enough for the correct operating of the device, while a current of 1.4A (power supply about 4 W) increases the deformation speed of the finger. Drawbacks are the reduced life of SMA wires and an overheating of the device itself.

Fifth test consisted in a simultaneous heating of the three modules, on the same direction (see figure 8) and final positions are similar to the positions obtained during the first test.

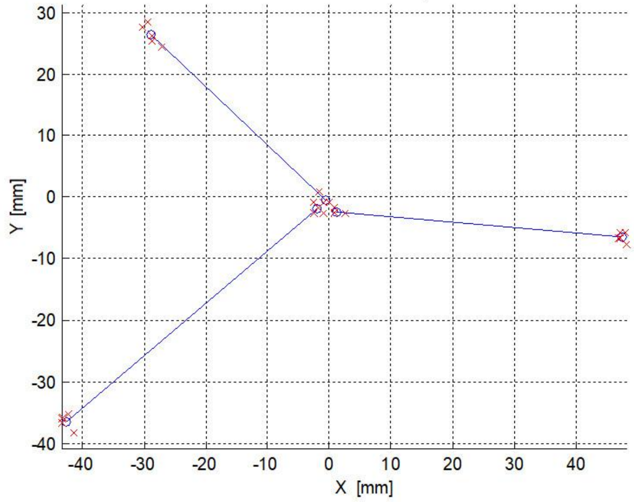


Figure 8: Simultaneous heating of the SMA wires for each main direction (fifth test)

Force tests

Test bench

The output force of the SMA actuator activated along its three main directions and three secondary directions was measured by means of a devoted test bench.

Figure 9 shows the test bench built to carry out the force tests. Two metal plates with suitable slots are orthogonally connected. The vertical slot, allowing to change the height position *d* of the actuator, fits the finger, placed parallel to the basement, with its axis horizontal; the horizontal slot lodges a Tekscan force sensor (ELF-BS26-20Z).

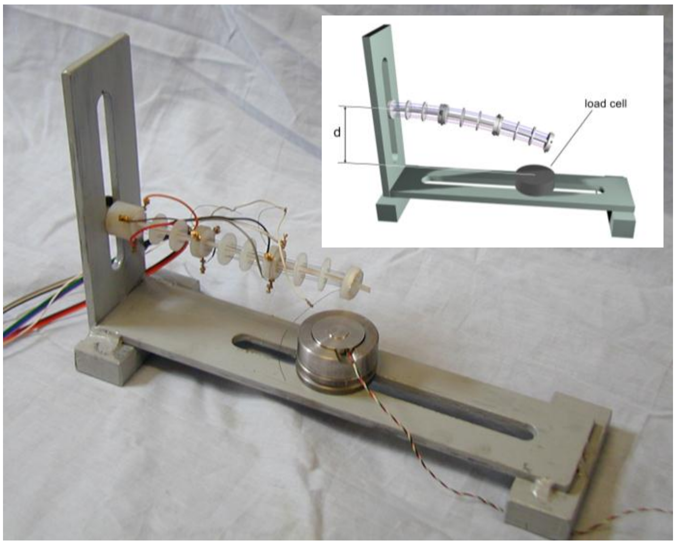


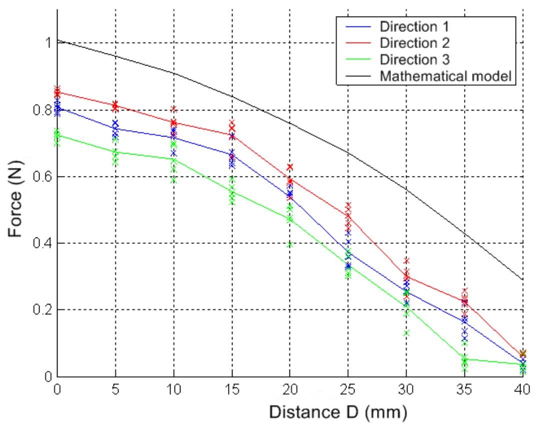
Figure 9: Second test bench, force tests

Test procedure and results

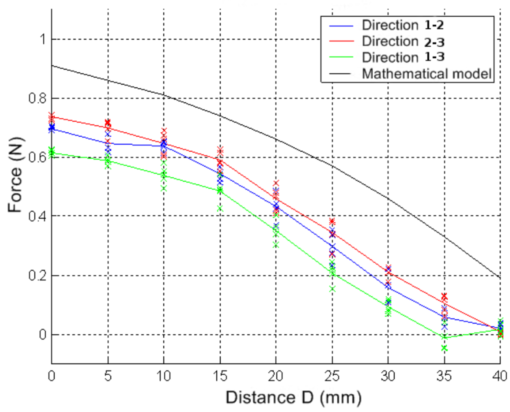
Similarly to the positioning tests, the force tests were divided in two separate sections: one for the force developed by the actuator when activated along the main directions, the second one along the secondary directions. Force values are measured for different values of the distance *d* between the actuator axis and the load cell upper surface (figure 9). The tests was carried out with step supply current of 3A, the three modules were simultaneously activated, activation time of 60 s, still air cooling. It was repeated 5 times per direction.

Figure 10 shows the force exerted on the load cell varying the distance d and the comparison with the mathematical model values. The continuous line represents the mean of the experimental single values (the colored crosses). In black, it can be seen the mathematical preview. The mean measuring error is about 6%.

It can be observed that the actuator output force along the three directions is different as above already explained, moreover that force is about 20% less than the mathematical model preview because the wires are not perfectly tensioned in unloaded conditions and perhaps the antagonistic wires determine a bias force bigger than the previewed one.



a)



b)

Figure 10: Force exerted on the load cell as a function of distance d a) main directions b) secondary direction

CONCLUSIONS

The designed and realized actuator shows stable and correct operation. The modular design of the actuator has proven to be very effective as it has made it possible to choose the size of the device as needed. The modules are made up of few elements for which the actuator is particularly economical to manufacture and this advantage would be even more pronounced in the case of serial production.

The small size of the device allows for a light and flexible structure, but at the same time manual assembly of the system is quite difficult. A possible improvement may consist of a new design for 3D printing of the body and for a more easy way to secure the SMA wires to the base.

From experimental tests, it has been found that the workspace is wide enough: planar projection is a circle of about 30-40 mm of radius. Unfortunately it has also been observed that the movement is not very regular along the various directions: to avoid this inconvenience, in a second prototype, much more attention should be paid to pretensioning of SMA wires.

Experimental force is about 20% less than the mathematical model force preview. This is probably due to manufacturing imperfections and frictions, however, they are encouraging results.

The compact design makes this actuator ideal for medical and mechanical applications, but it should be noted that required power supply of SMA wires is quite high. The cooling of the wires is a major problem, which reduces the operating frequency of the device. To overcome this inconvenience, forced ventilation can be added to the system. Electrical signal transmission should also be improved by inserting the cables into an outer sheath or by integrating them directly into each module.

Another interesting development of the actuator would be to provide it with a closed loop control of the end-effector position [29, 30]. To this end, the dependence of the electrical resistance of the SMA wires on the phase transformation stage could be exploited [9].

Nonetheless, the results achieved with this prototype are encouraging, especially considering the novelty aspects brought by SMA wires. Although there are some issues that seem to limit possible applications, many possible solutions can be identified when the search in this field will be more consolidated.

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