A Dexterous Robot Hand with Embedded SMA Actuators

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Abstract. This paper presents the design and implementation of a four-fingered human-size robotic hand intended for dexterous and grasping manipulation applications. The prototype hand has 3 degrees of freedom (DOF) per finger and 2 DOF in the thumb for a total of 11 DOF. Shape memory alloys (SMAs) micro-coils are embedded intrinsically within the hand structure to power the joints while exhibiting some advantageous features such as low-cost, lightweight, compactness and clean silent operation. To increase efficiency and decrease power dissipation, the SMA micro-actuators integrate magnetic bi-stable structures. Mechanical design, actuation approach and first prototype are presented and discussed.

Keywords: Bi-stable actuator, micro-coils, robot hand, shape memory alloys (SMAs)

1 Introduction

The human hand is a highly functional structure which roboticians have attempted to imitate for a long time. With its 21 degrees of freedom (DOF) (Fig. 1), 19 muscles, 17 joints, 19 bones, in addition to its ligaments, nerves and numerous sensors, the human hand is a very complex structure difficult to reproduce mechanically. Moreover, it is dexterous, stable and precise, but also fast moving, strong and flexible.

Over the past 20 years, a number of robotic hands have been developed for dexterous and skillful grasping applications in medical, welfare, space, industrial and virtual environments [1]-[5].

Traditionally, robotic hand designs have tended to be bulky, heavy and noisy due to the use of conventional actuation approaches such as electromechanical and pneumatic technologies. As a result of the problems inherent with these types of actuation, designers have been adapting various new actuation approaches for use in their place. It is believed that the use of smart materials such as shape memory alloys (SMAs), piezoelectric ceramics, electroactive polymers (EAPs) and electrorheological (ER) fluids will provide new design methodologies and paradigms for lightweight robotic hands.

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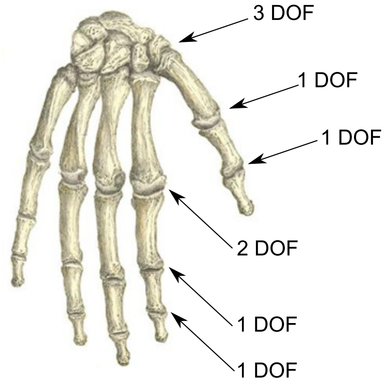


Fig. 1. Joints of the human hand with their corresponding DOF, after [6].

SMA technology seems to be one of the most promising candidates for the development of meso/micro actuators: compact size, high power/weight ratio, extremely high fatigue resistance to cyclic operation and smooth, clean, spark-free and noiseless performance make them an interesting actuation principle [7]. However, two major drawbacks are their relatively slow response speed and their non-linear behavior that make them difficult to control.

In this paper, we present the design and implementation of a robotic hand based on SMAs. The prototype hand is human-size, four-fingered and has 11 DOF. A SMA based micro-actuator intended for powering the fingers' joints is proposed. The actuator consists of an antagonist arranged pair of NiTi micro-coils, which integrates bi-stable structures to increase overall efficiency. This design approach permits to have all the actuators embedded intrinsically within the hand structure while keeping the prototype compact, lightweight, low-power consumption and low-cost.

The rest of the paper is organized as follows: Section 2 overviews the essential features of SMAs. Section 3 presents the design, characterization and implementation of a SMA bi-stable micro-actuator. Section 4 introduces the design of the robotic hand while Section 5 presents the first prototype developed and its grasping capabilities. Finally, Section 6 concludes the paper summarizing the main contributions and future work perspectives.

2 Essential features of shape memory alloys

The shape memory effect (SME) is the ability of a certain group of materials to "memorize" a specific shape when subjected to the appropriate thermal process. Materials exhibiting this effect are metallic alloys such as Ag-Cd, Au-Cd, Cu-Al-Ni, Cu-Sn, In-Ti, Ni-Al and the popular Ni-Ti (Nitinol) [8].

The SME occurs as a result of a temperature dependent transformation between two solid phases: high temperature *austenite* phase and low temperature *martensite* phase. Austenite phase contains the memorized or predefined shape of the material. When

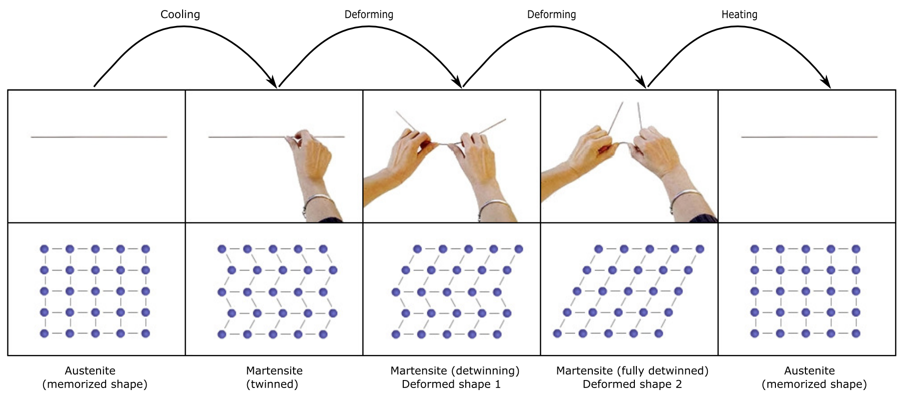


Fig. 2. The SME in SMAs at macroscopic and crystallographic levels.

cooled to martensite, the material presents very low stiffness and yield strength. It is quite malleable and can be easily deformed into a new shape, which it retains. Upon heating, the material returns to its austenitic original and pre-deformed shape (Fig. 2 top).

At microscopic level, the SMA's austenitic crystalline structure is highly symmetric and well ordered. Upon cooling, the crystalline structure collapses leaning in opposite directions along subsequent layers that are self-accommodating (or twinned) so that no macroscopic deformation results. Applying an external stress on the SMA will cause the twinned martensite layers to begin to lean in the same direction. When all the layers are leaning the same way, the SMA is said to be oriented (or detwinned). Upon heating, the crystal layers line up to recover their original symmetry (Fig. 2 bottom).

The SME is repeatable and it can be considered as a transformation phenomenon of thermal energy into mechanical work, usually generating force and displacement. Thus, SMAs can be used as active elements of actuators.

SMAs can be formed into almost any shaped actuator. Most popular shapes are wire, spring, tubing, sheet and ribbon.

Experimental testing of NiTi SMA straight wires has revealed that stroke is limited to approximately 4 to 5 % of their original length [9]. Compared to wires, coil springs do have a significantly higher recoverable strain. Impressive 300 % strokes can easily be obtained using helical springs. However, as they perform in torsion instead of tension, they cannot develop the same force.

This paper suggests that SMA coil springs can be designed to exert significant forces for powering robotic hands having at the same time, stroke and compactness not offered by straight wires.

3 A SMA based bi-stable micro-actuator

3.1 Material

A NiTi micro-coil spring was fabricated with trademark Flexinol wire ($Ni_{52}Ti_{48}$) with the following geometric characteristics: 200 μm of wire diameter, 1.3 mm of mean spring diameter and 12 active coils. Its mass is 30 mg and its laboratory cost is only 1 USD.

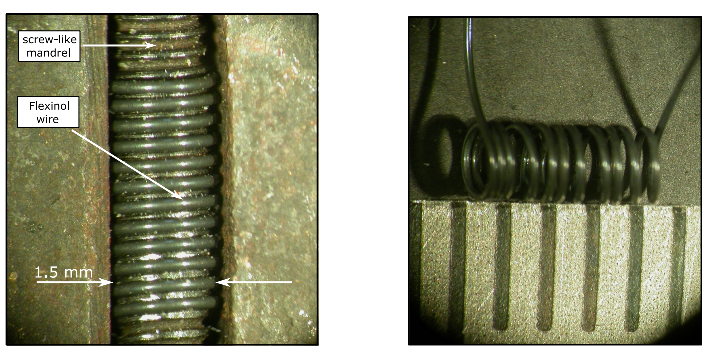
The coil shape was set by winding the wire tightly on a cylindrical mandrel (screw-like) and then heat-treating both wire and mandrel at 600°C for 5 min. Rapid cooling via water quench concluded the process (Fig. 3).

Differential scanning calorimeter (DSC) tests revealed that full austenite phase is achieved at 65°C while full martensite is at 36°C.

3.2 Performance Evaluation

The micro-coil's parameters were adjusted so that it develops an appropriate force according to its deflection and temperature. Fig. 4(a) shows the experimental load-deflection relations under various isothermal conditions for a maximum deflection of 10 mm. Note 2 different behaviors: elastic before load reaches a critical value and plastic beyond this critical value. The curves indicate that the maximum output force of the SMA micro-coil at a deflection of 10 mm is approximately 180 mN at 20°C, 410 mN at 85°C and 720 mN at 105°C.

Using this data, it is possible to formulate a 3D computational model of the SMA micro-coil's behavior in the load-deflection-temperature space (Fig. 4(b)) [10]. Note that, as introduced in fig. 4(a), the tensile force developed by the micro-coil against a load increases with temperature.



(a) (b)

Fig. 3. Fabrication procedure of an SMA micro-coil spring: (a) constrained Flexinol wire on a mandrel and (b) coil shape after heat treatment.

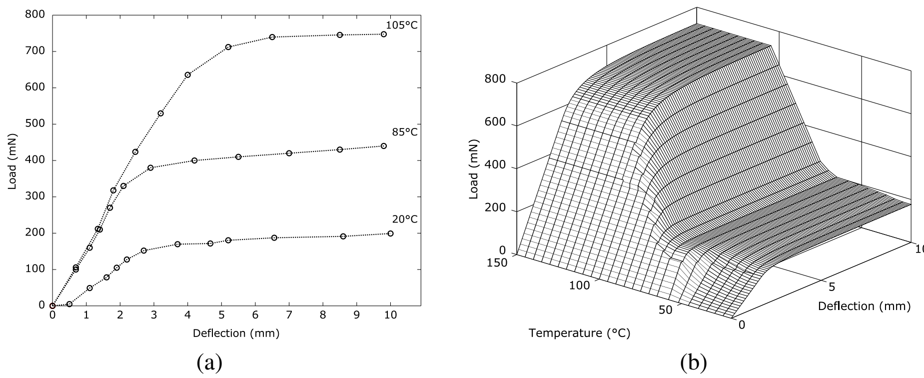


Fig. 4. (a) The micro-coils's experimental load-deflection behavior at constant temperatures (20, 85 and 105°C) and (b) computational model in the load-deflection-temperature space. Experimental observations revealed that beyond 105°C, the load-deflection behavior was practically the same.

3.3 Design of Actuators

As discussed in section 2, SMAs achieve their actuation through the phenomenon of the shape memory effect (SME), which is non-reversible. This implies that, a SMA itself cannot be considered as an actuator since it does not provide reversible motion.

Two general approaches are used to exploit SMA materials in actuator applications: the one-way and the two-way effect.

The one-way effect describes the ability of SMAs to recover a memorized shape when heated up to austenite, but retains this shape when cooled down to martensite. To be used in cyclic actuation, it is necessary to provide a biasing force to induce the initial deformed shape in the martensite phase.

The two-way effect describes a memory process with two stable shapes: one in austenite and the other one in martensite. Therefore, the two-way effect does not require any external mechanisms for cyclic actuation.

While using the two-way effect provides simpler and compacter actuators with many fewer elements involved, it certainly requires extra manufacturing processes, it is difficult to achieve correctly and its strain is only half of that observed in one-way SMAs [11].

Although a one-way effect SMA could be designed such that it exerts a force in three dimensions (when deformed in 3 directions from the memory configuration), the great majority apply a one-directional tensile force and cannot directly apply a compressive force.

In many robotic applications, this is accomplished by using a mass, an elastic element or a second SMA arranged in antagonist mode [12]. The simple mechanisms in fig. 5 show how these configurations can be used to design actuators that create linear motion.

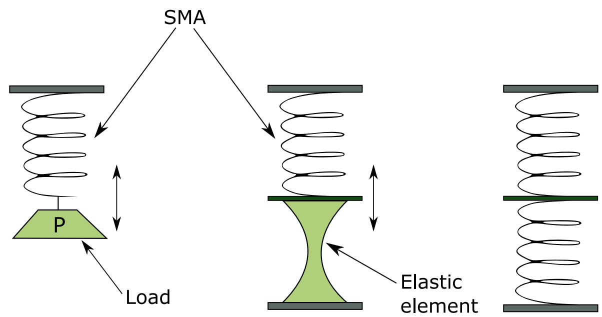


Fig. 5. Main SMA actuator configurations using one-way effect SMAs.

Note that all of these configurations provide motion essentially between two points defined by the active and passive states of the SMA. However, only the passive state can be considered stable since no power is needed to sustain it.

In contrast, the active state not only requires energy to be achieved but also to be retained; the SMA must be kept active, which not only leads to poor efficiency, but also implies serious drawbacks mostly when electrically heated.

In principle, an SMA can be heated arbitrarily quickly by passing a sufficiently large current through it. However, excessive electrical power has the capacity to overheat the SMA, causing thermal stress fatigue and a gradual degradation of its performance.

A strategy for retaining the active position in the martensite state of the SMA is then required to avoid power consumption, useless output work and overheating. One method to achieve two stable positions is the use of clamping/latching mechanisms. Thus, the actuator would need energy only when changing from one state to the other and in neither of the two end positions power would be needed.

If we consider that the hand's joints spend most of their time in a fixed position, it can be concluded that, actuators that spend a great deal of energy maintaining their active state are not acceptable. Bi-stable actuators are more suitable for this application [13].

In physical implementation, it is often advantageous to make use of bi-stable structures: they provide accurate and repeatable motion and, in presence of disturbances or environmental variations, they maintain the desired position [14].

4 Design of a SMA based robotic hand

The conceptual representation of a four-fingered anthropomorphic robotic hand is shown in fig. 6 left.

This design has 3 DOF per finger and 2 DOF in the thumb for a total of 11 DOF. Possible hand motions are shown in fig. 7. Note that the maximum joint deflection for this prototype is 90°. Thus, if all three joints are deflected 90°, the fingertip's total workspace will be 360°.

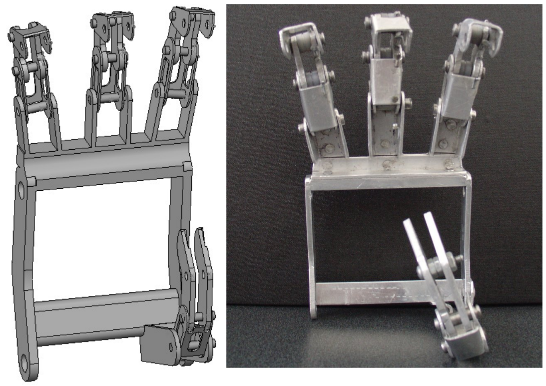


Fig. 6. Conceptual representation of a four-fingered robotic hand and its equivalent mechanical structure.

Fig. 6 right shows the equivalent mechanical structure. This structure is the same size as an adult's hand. Base and fingers were entirely fabricated using lightweight aluminum while joints are made of hardened plastic. Each finger link mass is estimated to be 35 g, so the entire finger is 105 g. The total structure is about 600 g.

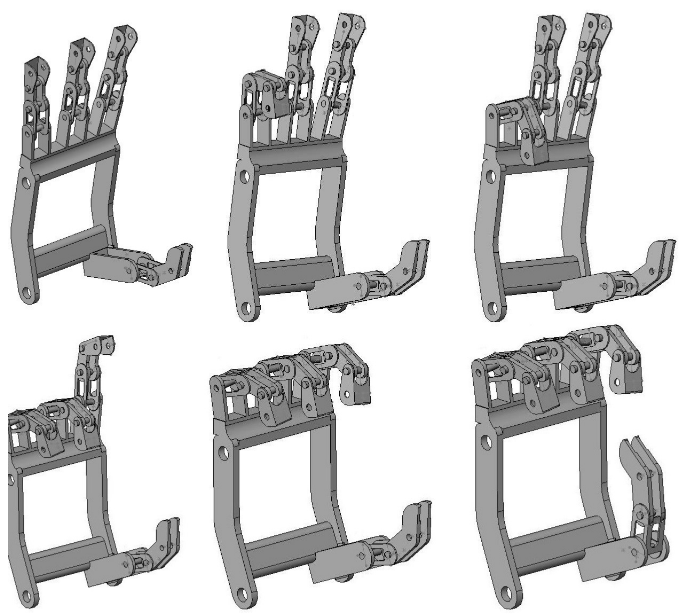


Fig. 7. Possible hand motions: 3 DOF per finger and 2 DOF in the thumb.

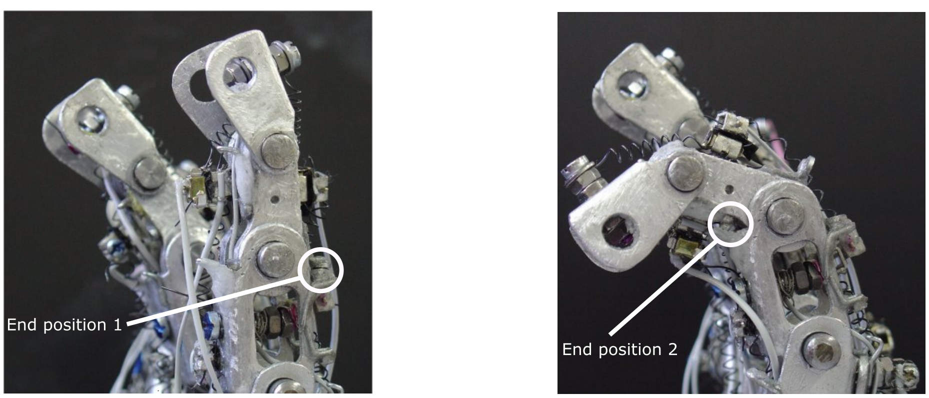
5 Prototype

The mechanical structure in fig. 6 is actuated by a set of SMA micro-coils of characteristics described in section 3. Note from fig. 4(a), that the micro-coil is perfectly capable of developing appropriate forces for powering the 35 g finger links when heated to 85°C. Furthermore, these micro-coils are quite small, so they can be embedded within the hand structure. No external actuation module is needed.

The SMA micro-coils were arranged in antagonist configuration. As seen from fig. 5, the antagonist principle is based on heating one SMA element at a time, so that its austenitic state produces a force and displacement over the second martensitic SMA. To retain the active position, the actuator integrate bi-stable structures.

Many mechanisms exhibit bi-stability: switches, closures, hinges, shampoo bottle caps, bicycle kickstands, tape measures, retractable pens, etc. [14]. A magnet approach seemed appropriate for incorporation into the robotic hand.

The operation principle is shown in fig. 8: (1) at the initial position, both SMA micro-coils are in martensite state. Position is retained by the magnetic attraction of two magnets (Fig. 8(a)). (2) When electrical current flows in one of the SMAs, its austenitic compressed memorized shape unblocks the magnets, extends the martensitic SMA and moves the joint until it reaches the second end position. Two other magnets are attracted ensuring this position and no further energy is required until a change is necessary (Fig. 8(b)).



(a) (b)

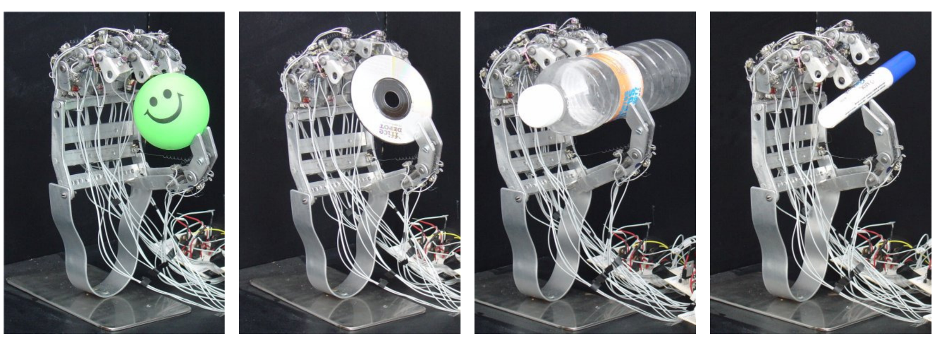
Fig. 8. SMA antagonist actuator with bi-stable structures. When one SMA micro-coil is heated, it shrinks and the link moves to one direction. When the opposite SMA is heated, the link moves to the opposite direction. End positions are ensured by the magnetic attraction of a pair of magnets.

The first prototype hand is shown in fig. 9. It is well known that SMAs cannot be welded, so they were mechanically fastened to the aluminum links. This also eases the replacement task: the micro-coil is simply unscrewed from the link and it can then be lifted out.

Fig. 9. First prototype of robotic hand with SMAs.

A total of 6 SMA micro-coils are embedded in each finger while the thumb contains 4. The entire hand encloses 22 SMA micro-coils or 11 antagonist pairs. A couple of wires are connected to each SMA to electrically control them from its electronic drive. Wire guides are included along the structure to avoid the risk of jamming.

Some grasping examples conducted with this prototype are shown in fig. 10. Note that objects in figs. 10(a)-(c) can be classified as "big" objects or power grasp as termed in [15] while 10(d) is a "small" object or precision grasp. Current work is focused on precision grasp to assist humans with objects difficult to manipulate.



(a) (b) (c) (d)

Fig. 10. Power and precision grasping examples: (a) sphere, (b) disk, (c) "big" cylinder and (d) "small" cylinder.

6 Conclusion

This paper has presented both design and implementation of a four-fingered human-like robotic hand intended for dexterous and grasping manipulation applications. The prototype proposed here uses non-classical types of actuation, such as SMAs, which allow the development of efficient, compact, lightweight and low-cost actuators.

An SMA based electrically driven micro-actuator intended for powering the hand's joints has been presented. This actuator uses an antagonist arranged pair of SMA NiTi micro-coils whose thermomechanical behavior has been characterized. To increase efficiency, ensure repeatability and decrease power dissipation, this micro-actuator integrates magnetic bi-stable structures.

The first prototype developed has 3 DOF per finger and 2 DOF in the thumb for a total of 11 DOF. It integrates 11 SMA antagonist actuators within its structure and is capable of grasping several kinds of objects. Current experiments involve precision grasping.

Future research perspectives include tele-manipulation based on electromyographic (EMG) signals. EMG signals will be measured from the operator's forearm muscles to detect finger motion. The prototype robotic hand is expected to move accordingly.

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