A Fuzzy Logic Control System for a Robotic Hand Driven by Shape Memory Alloy Wires

André F.C. Silva, Samuel de Oliveira, Andreas Ries, Simplício A. Silva, Cícero R. Souto

Abstract—This paper presents a robotic hand using wires with shape memory (NiTi) as non-conventional actuators. The mechanical structure of the robot hand was first designed by means of a CAD computer program and afterwards 3D printed using ABS polymer. The robotic hand was designed according to the physiological characteristics of the human hand, with particular attention to the angles formed by the phalanges of the fingers. A mechanical system accommodates the thin NiTi wires compactly, thus forming an artificial muscle. A fuzzy logic based control system allows an accurate positioning of each phalanx. The contribution of the present work to science lies in the practical implementation of known techniques and materials.

Index Terms—Shape memory alloy, NiTi, Fuzzy logic, Artificial hand.

I. INTRODUCTION

The human hand is a major challenge in the field of rehabilitation robotics due to its large number of phalangeal joints, providing great flexibility for performing numerous tasks. Hands characteristic ability to change shape and adapt to different types of objects, is supported by 23 degrees of freedom (DOF), five for the thumb, four for each finger and two more for the palm. This large number of DOF’s is related to 27 bones, 17 joints and 19 muscles of the hand as well as to a series of tendons activated by muscles located in the forearm [1]. The human hand is divided into fingers, which are subdivided into phalanges. While the thumb possesses only two phalanges (proximal and distal), the remaining fingers are composed of a proximal, middle and distal phalanx. Figure 1 gives an overview on the anatomy of the human hand.

With exception of the thumb, every finger has three joints, as illustrated in Figure 1. These joints permit the movement of the phalanges, which is mediated by tendons, connecting muscle to bone. Every joint can take a maximum angle, thus limiting the movement of the phalanges. Table 1 summarizes these limiting angles considering an adult hand.

The joint located closest to the metacarpal bone is called the metacarpophalangeal joint (MC). The proximal interphalangeal joint (PIP) connects the proximal and middle phalange,

![Fig. 1. Nomenclature of the anatomy of the human hand [2].](image-url)

while the distal and middle phalanges meet in the distal interphalangeal joint (DIP).

When thinking in terms of man-machine interaction, the intent to use artificial hands as prostheses rises new challenges such as comfort, easy handling and integration. Some robotic hands using conventional actuator systems have inherent problems with weight and noise, which difficult or restrict the robotic use [4], [5]. In order to overcome these problems, smart material structures based on alloys with shape memory have been widely explored. Capable of generating force and displacement, fine wired shape memory alloys with diameter less than 0.5 mm have been used as artificial muscles aiming at replacing electric motors and pneumatic actuators.

According to Terauchi et al. [6], it is possible to change the angles of the joints of the fingers by means of shape memory alloy (SMA) wires. A control electric current is used to induce a change in the SMA wire length. The literature lists few studies dealing with the idea of a robotic hand actuated by shape memory alloy wires.

An early contribution to robotic hand construction is the work by Bundhoo and Park [7] who developed an artificial finger driven by SMA wires simulating natural tendons. The focus of this work was the development of prostheses for children. The dimensions of the finger were: proximal phalanx: 34 mm, medial phalanx: 22.5 mm and distal phalanx: 18 mm. Those authors used SMA wires with a diameter of 0.582 mm to perform flexion as well as adduction/abduction movements

<table>
<thead>
<tr>
<th>Phalanx</th>
<th>Joint</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal</td>
<td>MP</td>
<td>90°</td>
</tr>
<tr>
<td>Middle</td>
<td>PIP</td>
<td>100°–110°</td>
</tr>
<tr>
<td>Distal</td>
<td>DIP</td>
<td>80°</td>
</tr>
</tbody>
</table>

TABLE I MAXIMUM ANGLES FORMED BY THE JOINTS OF THE FINGERS. NUMERICAL VALUES FROM REFERENCE [3].
of the MP joint. For flexion of the PIP joint a wire with a diameter of 0.69 mm was used.

Bundhoo et al. [8] developed an anthropomorphic prosthesis of a finger driven by special motors, the so-called Miga Motors. These are motors with a rolled up SMA wire in their interior, capable to generate displacements in the order of 9.5 mm with an output force of up to 22 N and an actuation time of 50 ms.

Silva et al. [9], [10] designed a prototype robotic finger driven by 0.31 mm diameter SMA wires. The finger was manufactured by rapid prototyping, using ABS (Acrylonitrile Butadiene Styrene), with 3 degrees of freedom. The lengths of the phalanges of the finger prototype were: 44.8 mm, 26.2 mm, 17.7 mm for the proximal, medial and distal phalanges, respectively. The maximum bending angles of the fingers were 90° for the proximal phalanx, 100° for the medial phalanx and 80° for the distal phalanx.

Farías et al. [11] constructed a hand with 4 fingers, one of them being the thumb; all fingers were activated by SMA micro-springs. Their hand had 2 degrees of freedom for the thumb and 3 degrees of freedom for each remaining finger. To perform the flexion and extension movements, 22 SMA micro-springs were combined, 6 for each finger and 4 for the thumb. The joints were designed to perform a 90 degree angle.

Recently, Lee, Okamoto and Matsubara [12] developed a prototype of a robotic hand with 5 fingers, each finger consisting of three phalanges. The thumb did not perform any active movement, since the other fingers performed two active movements and a passive movement, that is, the distal and medial phalanges were connected, while the proximal phalanges were independent. With this set-up, only two wires were necessary for activation. The return to the initial position after activation was achieved by means of springs.

This work reports a mechanical system for conditioning thin SMA wires (Ni-Ti alloy), assembled in a compact form, denominated in this work as Artificial Muscle (AM). The action of the fingers occurs through activation of the AMs, by an electric current. The activation causes a bending movement. The return of each bending movement occurs passively. Additionally, a fuzzy logic based controller is shown to be efficient for regulating the position of the fingers of the robotic hand.

II. MATERIALS AND METHODS

A. Hand design

The robotic hand developed in this project was designed for 13 Degrees of Freedom (DOF). The hand consists of 5 fingers, 4 with 3 DOFs each and the thumb with 1 DOF. Table 2 lists the values of the phalanges and the angles of the 4 fingers.

<table>
<thead>
<tr>
<th>Phalanx / Joint</th>
<th>Length</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal / MCP</td>
<td>50 mm</td>
<td>90°</td>
</tr>
<tr>
<td>Middle / PIP</td>
<td>40 mm</td>
<td>90°</td>
</tr>
<tr>
<td>Distal / DIP</td>
<td>40 mm</td>
<td>40°</td>
</tr>
</tbody>
</table>

Table 3 shows the values of each phalanx and the angle of the thumb relative to the palm.

The principal design feature is the actuation of the fingers by SMA (Shape Memory Alloy) wires. Actuation means execution of the bending movement. The return to the initial position is a passive motion due to rubber rings fixed at different locations of the phalanges.

In the resting position, the toes are slightly flexed at an angle of 40° (θp4 - angle of finger 4) in relation to the proximal phalanx and the palm, 15° (θm4) between the medial phalanx and the proximal phalanx, and 15° (θd4) between the distal phalanx and the medial phalanx. For the thumb, the medial phalanx is 25° (θpm - angle referring to the medial thumb) flexed with respect to the proximal phalanx and 20° (θpd - distal thumb angle) between the distal and medial phalanges.

An image with the arrangement of the mentioned angles is shown in Figure 2.

Figure 3 shows the prototype of the hand that was designed with the help of the CAD program. Simulations were performed in a virtual environment so that it was possible to identify some interference before the three-dimensional physical structure was constructed via 3D-printing.

It is possible to perceive from Figure 3 that the thumb stays in a position opposed to the other fingers. This position was defined as a way to minimize the 5 DOFs related to a human thumb.
B. Actuator design

Robotic hand prototypes using SMA wires as actuators require a relatively large wire length. The way to accommodate these actuators is always an obstacle for researchers. In this work, a prototype of Artificial Muscle (AM) was developed to accommodate the wires. Figure 4 sketches the developed AM prototype.

The construction shown schematically in Figure 4 is able to compact a length of up to 1500 mm of SMA wire. The AM makes use of a compression spring (with a stiffness of 47 N/m) at the top, in order to keep the SMA wires always under a mechanical stress. When activated, the SMA wire generates sufficient force to move the upper pin down, thereby achieving the displacement necessary to perform the angular movement of the phalanges. The pulleys that make up the mechanical assembly of the AM were made of Teflon. Figure 5 shows the forearm with the 9 AMs that are attached to the robotic hand.

The SMA Ni-Ti wires used as actuator in the AMs were purchased from the German company “Memory-Metalle” (trade name “alloy H”). The wire diameter was 0.31 mm; the material is destined to applications in actuators. The wires were heated for 20 minutes at 450°C in an electric furnace, followed by cooling to room temperature. This heat treatment eliminates part of the hardening and promotes the release of the reversible martensitic transformation that is responsible for the appearance of the shape memory phenomenon in Ni-Ti wires. After this treatment, the phase transformation temperatures of these wires were determined using a DSC calorimeter made by TA Instruments, model Q20. Slow DSC scans (5°C/min) revealed that the austenite phase forms upon heating between 74 and 85°C, while the transition from austenite to martensite occurs in the interval from 69 to 30°C upon cooling.

After the heat treatment, the Ni-Ti wires underwent a testing process for finding conditions to observe the two-way shape memory phenomenon, which leads to a self-contraction of the wire during heating.

C. Control system design

The use of a fuzzy logic control technique to actuate the robotic hand was motivated by some special characteristics of this methodology, such as: (I) natural and intuitive formulation trying to imitate the behavior of a human; (II) does not require a detailed knowledge of the elements of the process to be controlled (plant, sensors, actuators, etc.); (III) is applied to linear and non-linear systems, and finally (IV) is quickly implemented at low cost, besides presenting characteristics of robustness to uncertainties or parametric variations.

For the design of this controller, five triangular and two trapezoidal functions were used for the input variables as can be observed in Figure 6. These functions were adopted due to a previous knowledge of the system.

For the output variable, seven triangular and two trapezoidal functions were adopted, as can be observed in Figure 7.

The fuzzy method adopted was MAMDANI. The choice of this method was due to its wide applications and ease of use. In order to develop the basis of the rules, a table found in the literature [13] was taken as a starting point and some adjustments were made. The resulting rule base is given in Table 4.

The map of the rules shown in Table 4 refers to an associative matrix, which has an output depending on the combination of inputs, or from the existence of an output, the inputs can be determined. After tuning the fuzzy controller, using the development system for Matlab Fuzzy Logic Toolbox algorithms, several experiments were performed.

III. RESULTS AND DISCUSSION

Each finger was tested individually to subsequently activate the entire robotic hand. The first test corresponded to the appli-
cation of a current step to verify the maximum possible angle that can be obtained. The result obtained for the proximal phalanx of finger 3 is presented in Figure 8.

This experiment was repeated for all the phalanges of each finger. It can be noticed that all the proximal phalanges presented a residual angle after switching off the current. This fact occurs due to the existence of friction between the movable parts of the finger, as well as friction in the pulleys existing in the artificial muscle.

**TABLE IV**

Fuzzy IF-THEN RULES.

<table>
<thead>
<tr>
<th>Error/Err.Var.</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NVB</td>
<td>NVB</td>
<td>NVB</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>ZE</td>
</tr>
<tr>
<td>NM</td>
<td>NVB</td>
<td>NVB</td>
<td>NVB</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>NM</td>
</tr>
<tr>
<td>NS</td>
<td>NVB</td>
<td>NVB</td>
<td>NB</td>
<td>NM</td>
<td>NS</td>
<td>NM</td>
<td>NS</td>
</tr>
<tr>
<td>ZE</td>
<td>NB</td>
<td>ZE</td>
<td>ZE</td>
<td>PS</td>
<td>PS</td>
<td>NS</td>
<td>PS</td>
</tr>
<tr>
<td>PS</td>
<td>PM</td>
<td>PB</td>
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<td>PM</td>
<td>PM</td>
<td>PB</td>
<td>PVB</td>
</tr>
<tr>
<td>PM</td>
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<td>PB</td>
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<td>PM</td>
<td>PB</td>
<td>PVB</td>
<td>PVB</td>
<td>PVB</td>
</tr>
</tbody>
</table>

Having found the maximum open-loop angle of all proximal phalanges, the sensor (flexsensor) was installed at an adequate position, suitable for using the fuzzy logic technique. Then a
pre-defined sequence of angles was attempted to achieve. As an example, Figure 9 presents the desired (reference) angle and the true measured angle as a function of time for the proximal phalanx of finger 2.

It is worth mentioning that it is necessary to perform tests individually for each phalanx, since each finger has small differences between them, either in the dimensions or in the allocation of the artificial muscles. Such a careful investigation of each phalanx allows later to make small adjustments in the control system. For the proximal phalanx of finger 2, the highest error was 0.8° and the largest stabilization time was 25 seconds.

Equal experiments were repeated for the middle phalanges of all fingers. The result obtained for the middle phalanx of finger 2 is shown in Figure 10 and Figure 11.

The maximum open loop angle for the middle phalanx of finger 2 was 68°; it has been reached in approximately 10 seconds. Once this result was verified, the sensor is placed at an adequate location and the control system was adjusted. Figure 12 was obtained having considered the suitable sensor location. The middle phalanx of finger 2 stabilized slowest in 15 seconds with a maximum error in the permanent regime of 0.9°.

After actuating each phalanx individually, the complete hand was actuated. Figure 13 shows the image of the hand with the initial and final position of all fingers. Here, all artificial muscles, in the case of 9 of them, were subjected to an electric current of 0.85 A, without the use of a sensor.

When activating all proximal phalanges simultaneously to one single reference angle (see Figure 12), the error in the permanent regime is with approximately 1 degree quite similar for all phalanges. After 20 seconds, the hand has almost stabilized.

The activation of a sequence of desired angles (between 50° and 65°) for all proximal phalanges is presented in Figure 14.
For the sequence adopted above, the largest error occurred in the permanent regime of the forth proximal phalange, which was 1.7°. Similarly all middle phalanges were activated to one reference angle, which is displayed in Figure 15 as a function of time. In the permanent regime, the angular error of the middle phalanx of finger 2 is notably higher (1.5°) than that for the remaining phalanges. However, it is still in the same range of the error corresponding to the proximal phalanges (approximately 1°).

Figure 16 shows the simultaneous activation of all middle phalanges to different angular values. It can be seen that the phalanges exhibit differences in the velocity to reach the imposed final reference angle. This was mainly due to the friction caused by the differences in position of the artificial muscles at the base of the hand. However, some other factors contribute to these differences. These are the slightly different sizes of the fingers, the differences in friction of different joints, and the hand assembly in general. From Figure 16, the highest error of 1.3° was observed in the permanent regime for the second middle phalanx (time range 160-180 sec).

IV. Conclusion

In summary, a prototype of a robotic hand is presented. A control technique based on fuzzy logic was applied to affect the angular positioning of each phalanx. The maximum error reached by the system in a steady state was 1.7 degree, which is a permissible error for this type of application. Regarding the time to achieve the desired angular value of each phalanx, this prototype is similar to on thin-wire based SMA actuators found in the literature. However, when comparing the results with conventional technologies, it can be noticed that the prototypes of robotic hands driven by motors have superior behavior regarding the response time.

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