Mechatronics 91 (2023) 102957

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

A novel multi-wire SMA-based actuator with high-frequency displacement☆,☆☆

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ARTICLE INFO

Keywords:
Shape Memory Alloy actuators
Multi-wire actuator
Single-wire actuator
High frequency displacement
Position response

ABSTRACT

Shape Memory Alloys (SMA) are a group of metallic alloys that can return to their original shape when subjected to a temperature transformation between two phases. SMAs have been used as an alternative solution to conventional actuators in different applications of the robotics, biomedical, aerospace and automation domains because of their characteristics; being one of the leading solutions in different fields such as soft robotics and bio-inspired mechanisms. However, these actuators are still limited due to their operating frequency, their electrical efficiency, and their control performance due to their non-linearities. This paper presents a new multi-wire actuator structure based on SMA, with two different activation strategies. By combining the use of a multi-wire SMA in an alternative way, the overall recovery time is reduced. Thus, higher frequencies can be achieved in the reference signal. In this study, the effect of the diameter, geometry and activation temperature of the wires is evaluated in two different configurations. Firstly, when the actuator produces a linear displacement and, secondly, in an antagonistic configuration where the final displacement is a rotating movement. The results prove that the operating frequency of the multi-wire actuator increases considerably, when compared to the configuration where only one SMA wire is used. Moreover, it can be stated that the performance of the actuator improves when using wires with a thinner diameter and a higher activation temperature, with weights closer to the maximum force supported and a geometrical disposition of the wires that brings them as close as possible.

1. Introduction

Shape Memory Alloys (SMAs) are a group of metallic alloys that can return to their original form when subjected to a memorization process between two transformation phases; martensite phase at low temperatures with a smaller value of Young's modulus and a larger size according to Suresh et al. [1], and austenite phase at high temperatures according to Jani et al. [2]. Due to the molecular rearrangement in their crystalline structure when this transformation takes place, motion is created turning the system into a smart actuator.

These actuators have been developed due to the increasing need for miniaturized and lighter systems in different areas such as robotics, biomedical engineering and aerospace (removing 1 kg from all aircrafts operated by Lufthansa would save 30 tons of kerosene annually see [3]). The principal advantages presented by these materials are their high power to weight ratio, their silent, clean and spark-free operation and their design simplicity and easy miniaturization. Among their principal disadvantages, depending on the application, it can be observed a relatively small usable strain, low accuracy, low energy efficiency and, specially, low operational frequency, e.g. [4].

This operational frequency depends on the heating and cooling time, in other words, the time required by the material to contract and expand. The heating time can be easily reduced by increasing the magnitude of the actuation current; while the cooling rate is restricted by the rate of heat transfer to the environment surrounding the actuator, its shape and its size (which will also determine the loading capacity of the actuator). Consequently, there will also be a narrow relationship between the loading capacity of SMA actuators, its diameter and the

☆ This paper was recommended for publication by Associate Editor Michael Ruderman.

☆☆ The research leading to these results have received funding from the "Sistema robótico para propiciar la marcha en niños pequeños con Parálisis Cerebral" under Grant PID2019-105110RB-C32/ AEI/10.13039/501100011033, funded by Agencia Estatal de Investigación (AEI), Spain; from "Desarrollo de un actuador multihilo con fibras de SMA", funded by Arquimea Aerospace Defence and Security, S.L.U. Spain. Funding for APC: Universidad Carlos III de Madrid (Read & Publish Agreement CRUE-CSIC 2023), Spain.

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https://doi.org/10.1016/j.mechatronics.2023.102957
Received 1 December 2021; Received in revised form 11 January 2023; Accepted 28 January 2023
Available online 6 February 2023

cooling time required by it; the bigger the diameter, the higher the capacity and the longer it takes for the cooling process, according to Nizamani et al. [4].

Over the years, several studies have been conducted in order to reduce this cooling time and, consequently, increase the frequency at which this type of actuators can operate. For the purpose of understanding the techniques developed, a comprehensive literature review is given below.

Several authors have studied the effect of using forced air circulation as cooling media, e.g. [5–7]. It turned out to be an efficient method. However, it was not suitable for miniature applications and needed a higher power supply, as it was conducted through a fan or compressors e.g. [5,8,9]. According to Pathak et al. [6],Tadesse et al. [7],Cheng and Desai [10] the effect of using water circulation was also studied. It effectively helped reducing the cooling time needed by the actuator. Still, the boiling temperature of water and the increased system's complexity (a pump and special sealing arrangements are required) compromised these results, see [8–10]. Additionally, different studies with copper tubes and stainless metal tubes were driven, affecting the system flexibility according to Pathak et al. [6],Tadesse et al. [7].

E. g. Pathak et al. [6],Tadesse et al. [7] studied thermal grease as SMA heat sink. It significantly reduced the cooling time, but it involved heat loss during actuation, demanding a higher power supply in order to actuate the system, not been achievable in certain scenarios e.g. [5, 9]. Finally, they evaluated the effect of mineral oil as cooling media; which produced a significant improvement in cooling time whereas it had certain limitations such as sealing complexity and resistance to SMA motion due to oil viscosity, see [9].

E. g. [4] drove an additional experiment comparing those techniques (cooling in ambient air, grease and oil) they found feasible for this purpose. In this experiment they use the Joule heating method to activate the 0.15 mm diameter wires and measures parameters such as position, force, temperature and current. Actuating 1 and 2 s, the authors concluded that the cooling process was significantly reduced using oil and grease compared to the ambient air, but in these cases the power consumption increasing.

Different SMA multi-wire actuators were studied in [11–14]. They consisted of SMA wires following a multi-wire configuration which improved the operating frequency of the actuator. These projects suggest that, instead of using thick wires, which recover their initial form very slowly, parallel thinner wires can be used. Together, they can lift the exact same payload. An actuator made out of 48 SMA wires (0.15 mm-diameter) was staked in a parallel configuration between two plates see [11]. In this configuration, the whole actuator could lift more than 33 lbs (more than 72.75 kg) while working at high frequencies (to recover the initial form it needed approximately 1.7 s according to Dynalloy [15]) compared to 7 SMA wires in a parallel configuration which can exert a similar force with a 0.38 mm diameter and a recovery time of approximately 8.8 s. Unfortunately, SMA actuators following a parallel configuration present some limitations and disadvantages: the electrical efficiency of this type of actuator worsens; due to the SMA non-linear behavior, the wires do not always provide the same position response when activated by heating (a present issue on single and multi-wire actuators) and the stress inhomogeneity of the wires present on multi-wire actuators which can cause its breakage. Furthermore, depending on the bundle configuration, dry frictions and saturations can be detected, see [11].

Additionally, a bundle configuration actuator was used to actuate a finger in [12]. The actuator presents a bundle holder made out of a Perspex sheet with a thickness of 2 mm, and a single SMA wire with a length of 960 mm and a diameter of 0.15 mm distributed in a parallel configuration of 12 turns between the two bundle holders. Although the authors do not present a detailed analysis of the actuator's behavior, it can be observed how 1 s of actuation turns into a contraction of 3.45% of the actuators length; and how it recovers its original shape over a bias force in about 3 s. In this type of configuration, the force is distributed to each turn of the SMA wire, across the two bundle holders. Thus, it prevents the wire breakage alike the configuration presented before [11]. On the other hand, there are frictions due to the wires bending that makes it difficult for the actuator to contract and extend. Since the actuator is powered in series, a high voltage is required according to its data-sheet and due to the length of the wires. As a result, the actuator's displacement is limited to a few millimeters at most. A bundle actuator used on a soft five-fingered hand, was presented in [16]. In this work, thin wires of 200 μm diameter were mounted in parallel and activated by short pulses with high amplitude currents, providing a high speed actuation. In this case, the drawbacks are still the homogeneity of the wires' contraction and the high amplitude current needed by the wires, due to the parallel configuration. The amount of current consumption makes it difficult to integrate this actuator in certain applications, such as exoskeletons, exosuits or where the actuator is near to the human body.

Song et al. [17] presents a SMA actuator with a bending-twisting actuation mode. It consists of a layered reinforced structure with two bunches of thin SMA wires (38 μm diameter) on each side of this layer following a parallel configuration. Each actuator is fixed to one end and actuates alternatively the two bunches of parallel wires, resulting in a displacement of up to 120 mm at a frequency of 10 Hz in the opposite end. This actuator offers a high displacement at a high frequency when compared to other configurations, but the force of this actuator is very limited (a few grams). A precise control is also difficult to achieve.

All these examples (e.g. [11,12,16]) show just one duty cycle, where the heat accumulation effect in time cannot be appreciated and the cooling time of the actuator is every-time longer than that required according to the datasheet, except for the last one [17] where the actuator operates in an antagonistic configuration. Another examples of antagonist SMA actuator configuration can be found in [18–21]. In the majority of cases, the authors use thin wires moving light weights in exchange for a higher frequency response. Moreover, they only present a few continuous actuation cycles with a lower frequency than that recommended by the datasheet and tests are driven in a horizontal system without taking into account the gravity force. Finally, the actuator presented in this study aims to imitate human muscles where the strength of one muscle is different from that of its antagonist, working at high frequencies (higher from that on the datasheet) and presenting a flexible behavior.

An accumulative error occurs when the actuator is controlled in position and works at high frequencies — where the cooling time is lower than the cooling time recommended on the datasheet. Moreover, this issue is observed when the actuator works in an antagonistic configuration at high frequencies, see [13]. This error is smaller in the first cycles and increases due to the heat accumulation until stabilization, although a closed control loop is applied. This stabilization time depends on the stress and the wire diameter. This problem is more obvious when the actuator configuration includes additional structures, such as the Bowden cable, which provides flexibility, but also helps accumulating heat (if working continuously for several cycles).

This type of SMA-based actuators have turned out to be suitable for the soft robotics applications. Among the different applications where SMA was used as a soft actuator, it can be found an octopus arm see [22,23], a soft robotic neck see [24], a peristaltic soft robot, see [25] and a multi-DOF soft robot in [26]. Increasing the work frequency of this type of actuators will make them feasible for a wider range of applications in soft robotics.

As mentioned above, one of the main problems resulting from the use of SMA-based actuators is that they are activated by temperature. Particularly, the issue relies on the time required in order to cool down and recover their initial shape. An SMA wire can be activated quite fast and efficiently whereas their deactivation requires time for the SMA wire to properly recover its initial temperature (usually room temperature). This drawback prevents the SMA actuator from working at high frequencies. Even at low frequencies, performance can be improved.

The main goal of this research is to study different SMA actuator configurations in order to find the one that will exhibit a better performance even at high frequencies. The approach was based on the idea of using more SMA wires (in this study three) instead of one, and arranging their control in such a way that their cooling time will not imply an inconvenience. However, as long as a multi-wire actuator is to be used, the proposed solution should figure out the way not to worsen the electrical efficiency. Two main alternatives were considered: overlapping the activation of two wires (Control strategy 1) or activating one after the other subsequently (Control strategy 2). These control strategies will be explained in further detail all along this paper in Section 3.2 and their responses will be compared with each other, and with the one using only one SMA wire (single-wire actuator). They will also be compared with the reference signal that the actuator will be set to follow. Additionally, the influence of the main features of the SMA wire such as its diameter (0.31 mm and 0.38 mm) and its activation temperature (70 °C and 90 °C) will be investigated. Likewise, the SMA actuator will lift different weights in order to study its effect on the wire recovery.

Hence, this paper proposes a different structure for a SMA-based actuator with multi-wires. It can be optimized depending on the final application, for different payloads and working frequencies. The actuator does not use an additional cooling source and is not immersed in oil or grease. Thus, the flexibility of the actuator and, at the same time, its simplistic and clean structure are preserved. This actuator consists of three SMA wires separated in three PTFE tube and three Bowden cables which can be allocated inside a wider Bowden cable for a more compact structure. The multi-wire SMA-based actuator will be activated by two different two control strategies detailed in the section below which, when compared with others flexible SMA performances (with the same characteristics), present a better position response. Then, the algorithm that presents the better response will be used in a antagonistic configuration for the rotating movement. This last configuration could serve as an actuator for a lot of applications such as soft exosuits, presented in [27] or different soft robotics applications where an antagonistic displacement is needed.

This study, when compared to related works, presents a new solution to improve the SMA actuators' working frequency without using external elements (which can increase the actuator design and complexity) to decrease the cooling time and without using a bundle configuration (which presents a high intensity consumption and hampers the homogeneity of the wires' contraction). The solution consists in a multi-wire actuator where the wires' activation is alternated (potentially a energetically-safer, cheaper, more compact and lighter solution) with a flexible actuator that can also be used in an antagonist configuration. This approach presumes a promising solution for soft actuators and could be particularly advantageous for the users of this technology with regards to various influencing factors.

This paper is divided into six sections. Section 2 presents the methodology with a description of the actuator characteristics, the design of the actuators and the test bench where the tests were carried out. Section 3 provides the details of the control strategy and the tests setup, and Section 4 presents the results and analysis of multi-wire actuator compared with the single-wire actuator in linear and antagonistic configuration. Sections 5 and 6 introduces some discussions about the obtained results, the conclusions and future works.

2. Methodology

This section introduces the design of a SMA-based actuator with the multi-wires, the test bench (where tests with SMA actuators were performed), the electronics used in this study and the proposed test setups.

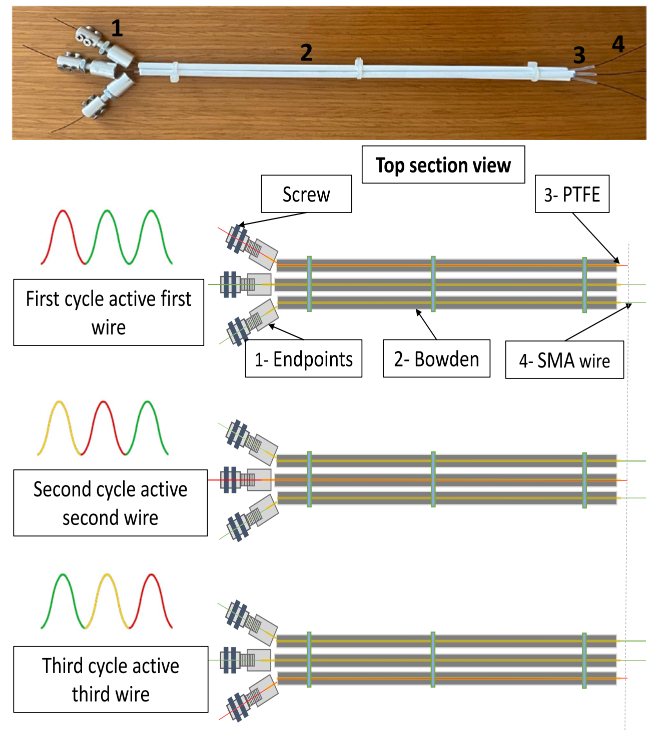

Fig. 1. Actuator design: top — real actuator structure; bottom — ketch of the actuator structure.

2.1. SMA-based actuator design

The proposed multi-wire SMA-based actuator consists of 3 SMA wires, each of one placed inside a PTFE tube, and each PTFE tube is placed inside a Bowden cable as shown in Fig. 1. Optionally (it has been done in this test), this multi-wire actuator can be placed into a Bowden cable with a larger diameter. The wider Bowden cable was also covered with an aluminium foil to make it easier for heat to dissipate.

The tests were carried out with SMA wires of a 0.31 and 0.38 mm diameter and a length of 1 m. In the case of the antagonistic configuration, due to the test bench structure, (to lift the test bench payload more than 22.5 N actuator force was needed) and for this was necessary to use actuators with a wire of 0.51 mm diameter and 1.16 m length. All experiments are performed at room temperature (22 °C). These diameters were chosen according to the research group objective, to introduce the actuator in the exosuits and exoskeletons.

The multi-wire actuator is inspired from the previous works [13] and it is shown in Fig. 1. It consists of:

- Element 1: Endpoints. They fix the SMA wire with the Bowden cable and serve as a linkage to the power supply.
- Element 2: Bowden cable. It helps with the transmission of the SMA force and with heat dissipation.
- Element 3: PTFE tube. It serves as an electrical insulator between the Bowden cable and the SMA wire. It also prevents frictions between the wires and the tube shell.
- Element 4: SMA wire. Its diameter can be changed according to the output force required.

When the SMA wire is subjected to a power source through the end points, it heats up due to Joule's effect and contracts as a consequence. As long as it is fixed to the end points, and thanks to its Bowden configuration, this contraction is transmitted to the edge emulating the performance of a muscle and allowing its utilization as an actuator in different applications such as exosuits, exoskeletons, prosthesis along with other applications in different areas.

Table 1
Properties of the SMA wires [15].

Diameter size [mm]	Resistance (R) [Ω/m]	Current (I) [A]	Force (F) [N]	Cooling 70 °C [s]	Cooling 90 °C [s]
0.31	12.20	1.50	12.80	8.10	6.80
0.38	8.30	2.25	22.50	10.50	8.80
0.51	4.30	4.00	35.60	16.80	14.00

The NiTi wires (55%–56% Nickel and 44%–45% Titanium) used in these tests have their activation temperatures at 90 °C or 70 °C according to Dynalloy [15]. The most important characteristics of these wires are gathered in Table 1. The electrical current column (I) refers to the estimated current needed for 1 s of contraction (the contraction time is directly related to current input). The last columns (Cooling 90 °C, Cooling 70 °C) refer to the approximate cooling time needed by the wire with activation temperature on 90 °C or 70 °C respectively to recover its initial shape at room temperature, in static air and using a vertical wire and a bias force (nominal deformation force). Moreover, Table 1 reflects this nominal force (F) and the electrical resistance (R) too.

Resistance was calculated based on the wires length according to the Dynalloy datasheet [15]. Finally, the voltage needed by each actuator configuration was computed using Ohm's Law and based on the intensity requirements also found in [15]. The 0.38 mm wire required 18.67 V whereas the 0.31 mm wire, 18.3 V and the 0.51 mm wire, 19.95 V. The activation was performed at a constant voltage.

The proposed actuator in this work was tested tracking sinusoidal references with different frequencies, in closing-loop position control. In this experiment, when the amplitude of the sinusoidal reference increase, the SMA actuator need to heat up to move a specific payload opposing to the gravitational force, and when the amplitude decrease, the SMA actuator need to cool moving the payload and having the gravitational force in its favor. The cooling time of the SMA wire is presented in the Table 1. According to this, to track a sinusoidal reference in position, the frequency of this sinusoidal reference is limited by the cooling time of the wire which in fact limits the performance of the actuator. For example, for a SMA wire with a diameter of 0.31 mm and an activation temperature of 90 °C, according to the wire needed cooling time, the actuator cannot track sinusoidal references which exceed 0.0735 Hz. All along this paper, the actuator's behavior working at higher frequencies is analyzed (with different configurations based on the wires presented in Table 1).

The Bowden cable can influence the cooling process in a positive way. When the SMA is activated for a short time and the Bowden cable does not have time to store heat, or in a negative way when the Bowden cable stores heat. In this study, the effect of the Bowden cable was not separately addressed.

2.2. Test bench and electronics

The test bench where the trials were carried out, consists of two subcomponents: a sensorized mechanical structure where the linear displacements tests were conducted in [13], Fig. 2 (top) and a sensorized rotative joint which permit to test antagonistic configurations Fig. 2 (bottom). The basic elements of the test benches are shown in Fig. 2 and described below:

- Element 1: Endpoints where the SMA wires are fixed.
- Element 2: Current sensor based on ACS723 and manufactured by SparkFun Electronics (Niwot, CO, USA) [28].
- Element 3: SMA-based actuator.
- Element 4: Magnet component necessary for the position sensor.
- Element 5: Temperature sensor, infrared thermometer - MLX90614 manufactured by Melexis (Ypern, Belgium) [29].

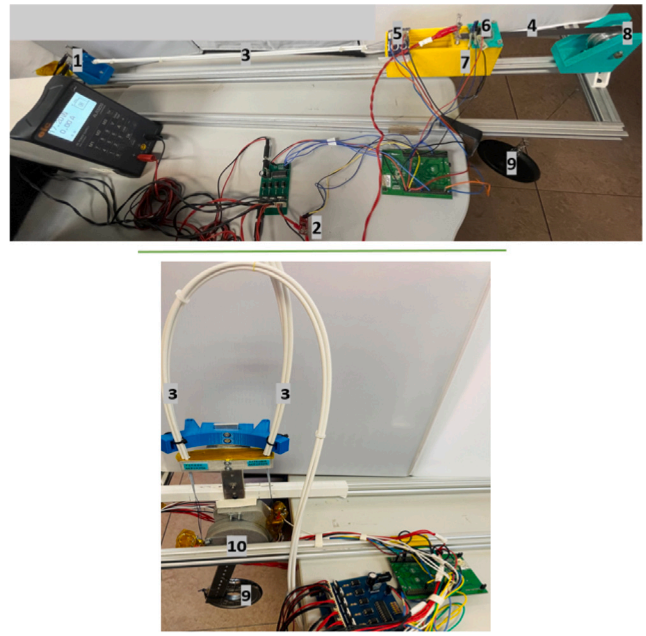

Fig. 2. Test bench: top — linear test bench configuration; bottom — rotative test bench for antagonistic movement.

- Element 6: Position sensor that measures the actual position of the mobile part. It is a NSE5310 position sensor manufactured by ams AG, (Styria, Austria) [30].
- Element 7: Mobile part of the actuator.
- Element 8: Pulley fixed to the test bench, so that a standard wire can move properly.
- Element 9: Weights lifted by the actuator.
- Element 10: AS5045 rotary position sensor manufactured by ams AG, (Styria, Austria) [30].

The objective of the test bench is to support and measure the actuators movement (linear and rotative) when lifting and lowering different weights. The power source where the actuator is connected must be set to the appropriate voltage, powering the actuator with an electrical energy which is transformed into heat by Joule effect. Finally, heat triggers the wires contraction and, thus, the weights' lift while the position sensor measures the displacement of the aforementioned mobile part. When the wire is not powered, it can recover its initial shape due to the cooling effect.

To control the actuator, a STM32F407 Discovery microcontroller from STMicroelectronics (Geneva, Switzerland) was used along with a power electronics circuit, see [13]. This circuit, based on a STMicroelectronics STP310N10F7 transistor (Geneva, Switzerland) and manufactured by ST [31], is activated with a pulse width modulation signal coming from the control software. For the linear movement test bench, the power stage presents 4 channels which can independently control 4 wires of SMA. For the antagonistic movement test bench the power stage have 6 channels. All along this project, only 3 channels are used for the linear configuration, while all 6 channels are used for the antagonistic configuration.

The linear position sensor used for capturing the performance of the actuator is a NSE3510 position sensor with a 0.488 μm resolution manufactured by ams AG, (Styria, Austria) [30]. Every component for the linear displacement configuration is connected to each other and can be seen in Fig. 3. The control algorithms were fully programmed in Matlab/Simulink, see [32].

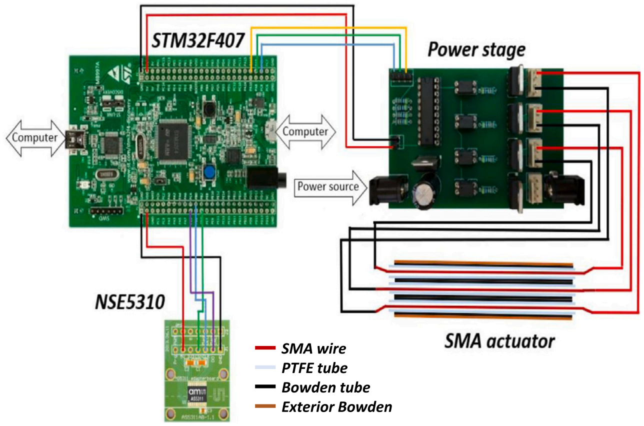

Fig. 3. Electronics hardware.

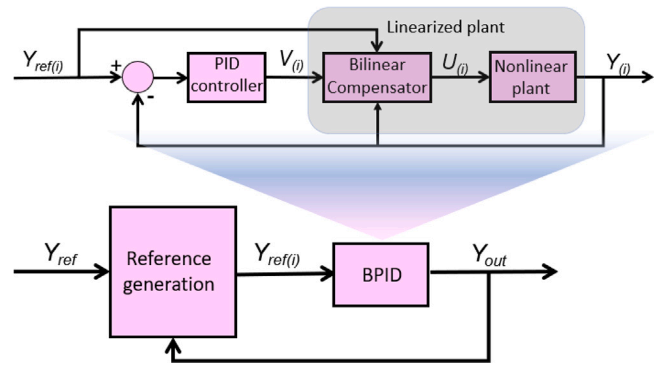

Fig. 4. Control Block Diagram: BPID controller for the proposed actuator.

Table 2
BPID Controller gains.

Gain	Kp	Kd	Ki	Kb
Value	24	2.4	0	2

3. Experimental tests in linear displacement configuration

The testing process will consist in observing the position response of the multi-wire actuator to a given sinusoidal reference signal, under a closed-loop control. Such signal represents the repetitive lifting of the weights connected to one endpoint of the actuator (the other end is fixed). The phase of this signal is $\pi/2$ whereas its amplitude and bias are both 30000 sensor units (14.64 mm). This translates into a 29.28 mm total displacement in height of the weights (peak-to-peak amplitude). The frequency of this reference signal will be set to 0.63 rad/s or a 10-seconds-per-cycle period for the first experiments. All the experimental tests was performed at an ambient temperature room of approximately 22 °C.

The testing process will consist of four types of experiments depending on the subject of study: the diameter of the wires, their activation temperature, the frequency of the reference signal and the geometrical disposition of the wires. For the first case of study, four different sets of weights will be tested for each wire diameter (0.31 mm and 0.38 mm) while both proposed control strategies, which will be explained later in this section, are compared to the performance of one SMA wire actuator-single-wire actuator. For the second test, the best-performing control strategy and wire will be selected and, then varying the weight, both activation temperatures (70 °C and 90 °C) will be tested. Finally, the wire and the control strategy that exhibit the best behavior will be tested, for the same weight for different frequencies.

The control strategies that combine the use of three SMA wires are presented in the next Section 3.1.

3.1. BPID control

The algorithm that guides the actuators is quite complex due to the characteristic hysteresis of SMAs (the transformation from martensite to austenite is different than the reverse process) and its non-linearities according to Savi [33]. SMA actuators are based on thermomechanical phenomena that make it too difficult to accurately predict their response. Various approaches can be found in the literature for the control of SMA, among other PI controllers. In the previous works of this research group see [13,34] the good results of a PD and BPID control law for the position control of an SMA actuator have been demonstrated. The thermal effect of the SMA wire is analogous to an integrating effect and, consequently, the integrating effect of a PI law does not improve the behavior of the actuator. The integrating effect of the PI law tends to eliminate the error in the stationary state, but in this case that is not the control problem, by making the actuator work in the appropriate ranges, it is possible to follow the reference without error. The main objective of the control is to improve the dynamic behavior of the actuator (following sinusoidal references in this case) and for this the derivative effect of the PD controller proves to give better results. Nevertheless, the control algorithm applied to the actuator (single-wire and multi-wire actuator) is a Bilinear Proportional Integral Derivative (BPID) controller schematically shown in Fig. 4 and based on the literature, see [13,35,36]. According to this biography, the PD controller presents more noise which can affect the actuator life long-term, for this reason the BPID solution was implemented.

Fig. 4 represents the control scheme of the actuator used in the test bench, where the Y_{ref} is the actuator desired position (common for all the wires), $Y_{ref(i)}$ is the independently reference of each wire of the actuator. This is generated according to the control strategy presented on the next section. $V_{(i)}$ is the control signal generated by the Proportional Integral Derivative (PID) controller, $U_{(i)}$ is the control signal rectified by the bilinear term, $Y_{(i)}$ is the response position of each wire (it is not measured in this experiment), and Y_{out} is the actuator position (mobile part position or element 7 presented in Section 2.2) measured by the test bench position sensor.

The discrete equation (with a sample time of 0.002 s) (Eq. (1)) of the bilinear compensator is as follows:

$$\frac{U(z)}{V(z)} = \frac{1 + k_b Y_{ref}(z)}{1 - k_b z^{-1} Y(z)}, \tag{1}$$

where K_b is the bilinear gain, $Y_{ref}(z)$ is the actuator desired position, $Y(z)$ is the response position, $V(z)$ is the control signal created by the PID controller and $U(z)$ is the signal rectified by the bilinear term. The PID controller is described by Eq. (2):

$$V(z) = [k_p + k_i T_s \frac{1}{z-1} + k_d \frac{N}{1 + N T_s \frac{1}{z-1}}] E(z). \tag{2}$$

where K_p is the proportional gain, K_d is the derivative gain, K_i is the integral gain and $E(z)$ is the error.

The BPID controller was tuned by trial-error method obtaining the controller gains presented on Table 2.

The main idea governing the behavior of the actuator is: establish when to activate and deactivate each wire according to the actuator reference and its actual position. Each wire's activation signal is associated to the previously mentioned PWM signal, which is proportional to the error signal of each control loop.

3.2. Control strategies

Concerning the algorithms that determine when to activate and deactivate each wire, two control strategies were proposed. Control

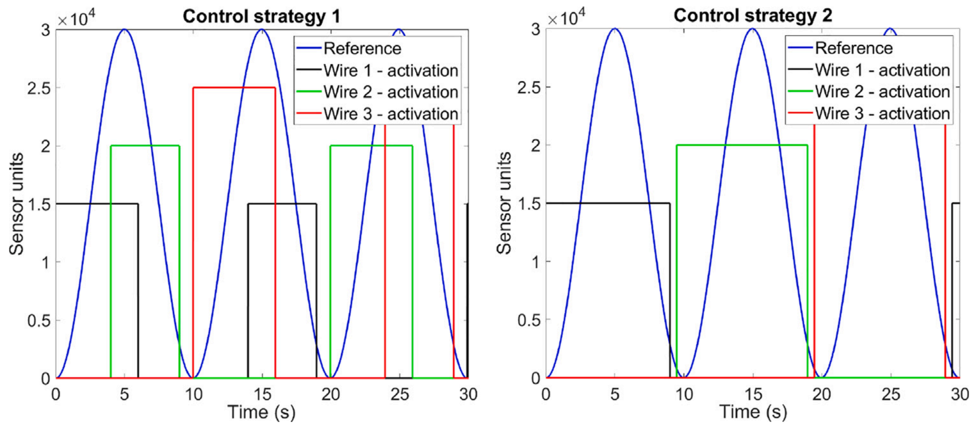

Fig. 5. Control strategy 1 (left) and Control strategy 2 activation (right).

strategy 1 suggests that the actuator performance can be increased by using two SMA wires at the same time during each cycle alternatively. On the other hand, Control strategy 2 focuses on allowing each wire to cool down properly and, thus, uses only one wire per cycle, again in an alternately way. Different actuation span times were tested but the ones shown in Fig. 5 were found to be the adequate option in terms of position error during the cooling stage. When one wire is activated, the BPID controller manage its energy and according to this, its cooling and heating process. During the activated stage, presented in Fig. 5, the SMA wire is governed by the PID controller. This can be heating according to the BPID control signal but also can be cooling for example if the controller signal considerably decreases or is 0. Also, when a wire is deactivated the BPID controller output is forced to 0. The energy which each SMA wire receives is provided by the power stage according to the BPID controller output signal.

Fig. 5 schematically shows the best version of each control strategy, with the actuator following a sinusoidal reference. Both strategies will be explained in detail below:

- Control strategy 1: When the cycle begins, the first wire is activated until 40% of the cycle duration and, then, the second wire is activated. Both wires work together until the 70% of the period has been reached and then the first wire is deactivated. For the next 20% (until 90%) the second wire is activated and then deactivated.
  During the last 10% of the cycle neither wire is active because it will only increase the thermal inertia that this tests aim to reduce. The process is repeated continuing with the wire that was deactivated first (it stayed deactivated the longest). The reason why those two wires are active together during that particular part of the cycle is due to the fact that it is the most demanding period (when weights are higher).
- Control strategy 2: When the test begins, the first wire is activated until 80% of the cycle is reached and, then, it is deactivated. No wire is working until 90% of the cycle, when the second wire is activated until 80% of the second cycle, and so on.
  This control strategy focuses on leaving a larger amount of time for the wires to cool down so that, then they must work again, their initial shape is properly recovered.

The activation percentages for each Control strategy have been set according to the proposed sinusoidal reference and the SMA wire behavior after several empirical tests where we vary the activation percentages according to the actuator response. The percentage variation of all the performed test are presented in the Table 3.

According to the SMA wire behavior to reach the activation temperature the wire needs some time for heating, for this the wire activates before the cycle starts, and in the last section where the wire needs to cool, to avoid the heating we deactivate the wire.

Table 3
Empirical tests for percentage adjustment.

Control strategy 1			Control strategy 2	
wire 1	wire 2	wire 3	wire 1	wire 2
60%	60%	100%	80%	90%
40%	70%	90%	95%	100%
40%	65%	100%	90%	100%
40%	60%	100%	90%	97%
40%	70%	90%	90%	95%
40%	60%	90%	90%	92%
35%	70%	95%	90%	90%
35%	60%	100%	85%	100%
35%	60%	90%	85%	95%
35%	55%	95%	85%	90%
33%	60%	90%	85%	85%
30%	75%	95%	80%	95%
30%	65%	95%	80%	90%
30%	60%	100%	80%	85%
30%	60%	90%	70%	80%

The expected outcome of the next tests is to check out whether using two SMA wires at the same time or one after the other is efficient as well as to prove if the high activation temperature version of a 0.31 mm diameter wire performs better due to its lower cooling time (see Table 1).

4. Results and analysis

In this section the principal results of the proposed configurations, in open-loop response and closed-loop response with the BPID controller are presented.

4.1. Open-loop response

To highlight the capabilities of the proposed system, the single-wire actuator and the multi-wire actuator (with Control strategy 2) response performance was compared in an open-loop. Also, to compare with the literature, e.g. [37] an equivalent force actuator was built using more thin wires. According to the available wires in our laboratory, we used wires with a diameter of 0.51 mm and 0.31 mm for this experiment. All the tests from this subsection were done in open loop, with wires of 1 m length, with Bowden cable, to maintain the flexibility properties of the actuator, and were subjected to the step input. The tested actuators were:

- Single-wire actuator with Bowden cable based on one wire of 0.51 mm. The total force of this actuator was around 35.6 N and the current activation according to the datasheet [15] was 4 A.

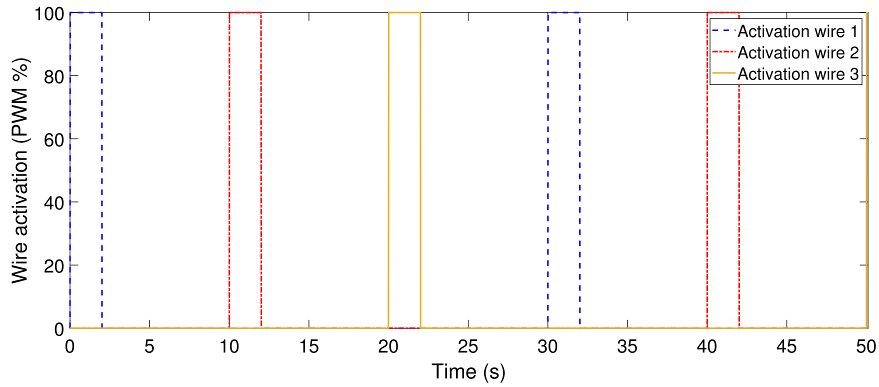

Fig. 6. Open-loop actuator activation.

- Multi-wire actuator with Bowden cables based on three wires of 0.51 mm activated with the Control strategy 2. The total force of this configuration was around 35.6N and its current activation according to the datasheet was 4 A.
- Thin-wires of 0.31 mm in parallel configuration, inside one Bowden cable. The total force of this actuator was around 38.4N and the current activation according to the datasheet was 4.5 A.
- Thin-wires of 0.31 mm in parallel configuration, each wire inside in an independent Bowden cable. The total force of this actuator was around 38.4N and the current activation for this configuration according to the datasheet was 4.5 A.

Each configuration, according to the datasheet [15], was activated with 4 A or 4.5 A, which on the controller represents 100% of PWM for the power stage. The single-wire actuator and the thin-wires configurations were activated cyclically each 10 s, where the first 2 s (from t = 0 s until t = 2 sec) the wire (wires) is activated, heating by Joule effect, and the last 8 s (from t = 2 s until t = 10 s) the wire (wires) is deactivated (cooling). For the multi-wire actuator, the wires have been alternatively activated in such a way that we obtain the same displacement such in the single-wire case. If the 30 s represent one activation cycle of the multi-wire actuator, the first wire was activated from the t = 0 until t = 2 s, the second wire was activated from t = 10 until t = 12, and the third wire was activated from t = 20 until t = 22 s, the rest of time the all the wires are deactivated. The periods of activation for the multi-wire actuator, are presented on Fig. 6, where the 100% PWM represents 4 A or 4.5 A current for the wire /wires.

The actuators displacement response subjected to the same step input signal, with the maximum current in open-loop, is represented in Fig. 7, where the red signal represent the response of the multi-wire actuator, the blue signal represent the response of the single-wire actuator, the magenta signal represent the response of the three thin-wires in parallel configuration where the wires are inside to one Bowden cable and the green signal represents the response of the thin-wires actuator where each wire was introduced inside of a independent Bowden cable. The thin-wires actuators present more displacement compared with the single wire actuator and multi-wire actuator in the first cycle, but its displacement decrease in the next cycles.

In Fig. 7, it can be observed that the displacement of the single-wire actuator and the 3 thin-wire actuator in the same Bowden cable decrease considerable in the first 100 s, among others, due to the heat accumulation effect in the Bowden cable. In these two cases, it was decided to stop the experiment after approximately 100 s. Comparing the actuation cycle in second t = 100 with the second actuation cycle t = 10 where the actuators present the maximum displacement, the actuator displacement in case of the 3 thin-wires inside of the same Bowden decrease 90.84% and for the single-wire actuator decrease 75.61%.

The displacement for the last two configurations, multi-wire actuator and thin-wire actuator when each wire is inside of independent Bowden cable, have been tested continuously working for 600 s. Similar to the first two configurations, the displacement decrease was calculated comparing the second cycle of actuation with the cycle in second t = 600. After 600 s of continuously working, the displacement of the multi-wire actuator was decreased 22.05% and the displacement of thin-wire actuator, where the wires are in independent Bowden cables was decreased 71.95%.

The non-uniform position response (the same magnitude in all cycles), although the wires are subjected to the same input current, is due to the wire non-linearity response and the wire setup in the test bench (do not have the same pretension, a limitation of the test bench). This cannot be observed in the closed-loop control where the position error can be canceled.

4.2. Closed-loop response

This section presents a summary of the results obtained after tests were driven in closed-loop. The results are gathered as a comparison of the average error between the response signal of the given control strategy (a single-wire actuator, a multi-wire actuator with Control strategy 1 and a multi-wire actuator with Control strategy 2) for each actuator configuration (in linear o antagonistic configuration) with respect to the reference signal. This error is presented in sensor units and the reference signal is 60000 sensor units (29.28 mm). In the following we refer to the multi-wire actuator with the activation Control strategy 2 as Control strategy 2, and to the multi-wire actuator with the activation Control strategy 1 as Control strategy 1. Also, in this section the effect of the wire's pre-tension is presented. The actuator set-up on the test bench tensed or less tensed, affect the position response of the actuator. According to this, several experiments will be carried out to analyzing:

- The effect of the wire's pre-tension.
- The effect of the wire diameter lifting different payloads.
- The effect of the wire activation temperature lifting different payloads.
- The effect of the working frequency on the actuator response following the sinusoidal reference.
- The effect of actuator geometry in its response.
- The antagonistic configuration using the multi-wire actuator.

4.3. The effect of the wires pre-tension

SMA wires provided by Dynalloy, have two different activation temperatures (70 °C and 90 °C respectively). Dynalloy datasheet [15] presents the inner temperature of each wire versus the strain suffered when subjected to an external load. This performance can be divided into 3 main areas. In the first and third areas (below 0.8% and above 3.8% of strain), the temperature difference is significant whereas the SMA wire suffers a reduced displacement when compared to the second

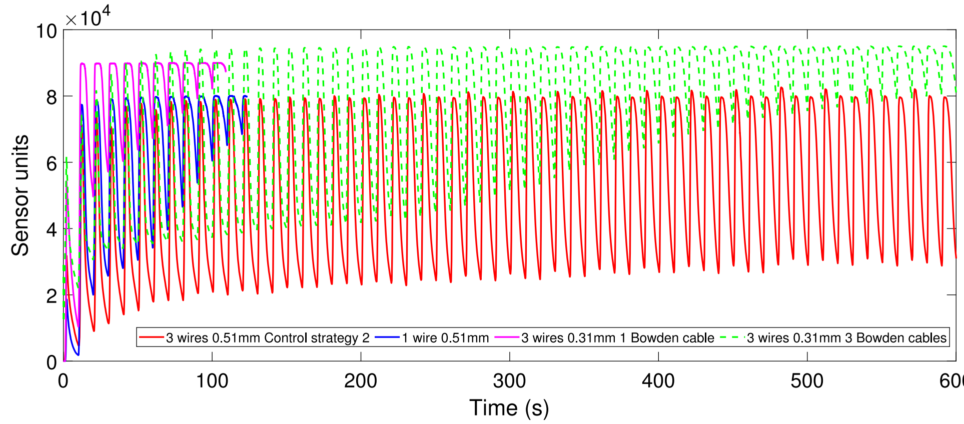

Fig. 7. Open-loop actuator response.

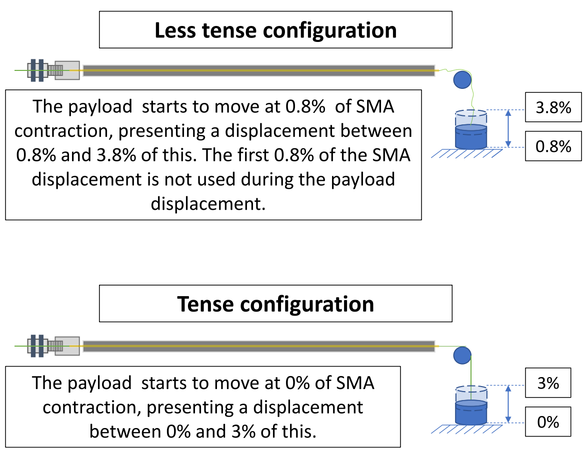

Fig. 8. Schematically representation of the less tensed and tensed actuator.

area. Furthermore, the ratio strain/temperature reveals a better performance in this second section (area), providing a strain of approximately 3% of its length with a temperature difference, approximately 15 °C.

Hence, the main idea is to work with the proposed actuator sticking to the second area. This way, the actuator needs to be deformed between 0.8% and 3.8% approximately of its initial length. Working in this area involves some advantages and disadvantages:

- Working below 3.8% of strain avoids an excessive energy consumption with regard to the small displacement achieved. The actuator activated by Joule effect above 3.8% presents a higher energy consumption due to temperature requirements.
- Working above 0.8% of strain avoids a slow recovery of the actuator. Temperature difference is remarkable in this area, and close to room temperature towards the end.
- There is some actuator displacement that remains unused. Hence, the SMA wire is over-dimensioned.

This test was driven with the linear configuration using a single-wire actuator with a diameter of 0.51 mm and 90 °C activation temperature. This configuration was mounted in the linear test bench, Fig. 2 - top, with a constant 3 kg payload. Firstly, a wire baring a lower tension force (less tense) was set in order to work between 0.8% and 3.8% of its strain. Afterwards, the wire was pre-tensed to enabling a strain between 0% and 3%. Schematically this two configuration can be seen in Fig. 8.

In the first case, even though strain starts in 0%, the effective payload displacement measured by the sensor starts in 0.8%. Therefore, the payload 0 position matches the actuator's 0.8% strain. The results of these two tests are shown in Fig. 9.

Fig. 9 shows that the position error is lower in the first case (lower tension) than in the second one. Furthermore, the higher error produced by both of the actuators is due to the higher operating frequency (0.1 Hz). A SMA wire with a 0.51 mm diameter needs 14 s (0.07 Hz) to cool down and recover its initial shape.

4.4. *The effect of the diameter*

This set of experiments was carried out to both, find the diameter of the wire that exhibits a better performance, and to identify the most efficient control strategy in terms of position response. Moreover, it will be decided whether the best control strategy can be applied to different diameters. Twelve tests were performed for each diameter (0.31 mm and 0.38 mm), the activation temperature for both is 70 °C and the period of the reference signal is 10 s. Different sets of weights were used for each wire as they have a different maximum force (12.8 *N* and 22.5 *N* respectively as presented in Table 1). Such weighs were: 0.5 kg, 0.75 kg, 1 kg and 1.25 kg for the thin wire and 0.5 kg, 0.1 kg, 1.5 kg and 2 kg for the thicker one. The operation of the multi-wire actuator has tested with the two control strategies previously described and compared with a single-wire actuator during the whole experiment.

Fig. 10 shows a graphical comparison between the average error of each control strategy: a single-wire actuator (black), Control strategy 1 (red) and Control strategy 2 (green) for two different diameters: 0.31 mm (lighter colors) and 0.38 mm (darker colors) when lifting four different weights with respect to the reference signal.

Fig. 10 shows that Control strategy 2 (green) improves the performance with respect to the use of the same SMA wire (single-wire actuator) every time (black and gray) regardless of the diameter. With regard to Control strategy 1 (red), it performs much better than the single-wire actuator for the thin-wire case but, for the thick wire, the difference is not appreciable. All in all, Control strategy 2 made out of thin wires (light green) exhibits the best performance as long as its error is the lowest. Regarding the weight, it can be deduced that the higher the weight the smaller the error. This decaying tendency can be observed regardless of the fluctuations with weigh that some curves exhibit because they are rather small when compared to the peak-to-peak amplitude of the reference signal, 60000 sensor units (29.28 mm).

From these tests, Control strategy 2 (one wire per cycle alternatively) using thin wires (0.31 mm diameter) was chosen for the next set of experiments where the effect of the activation temperature will be examined.

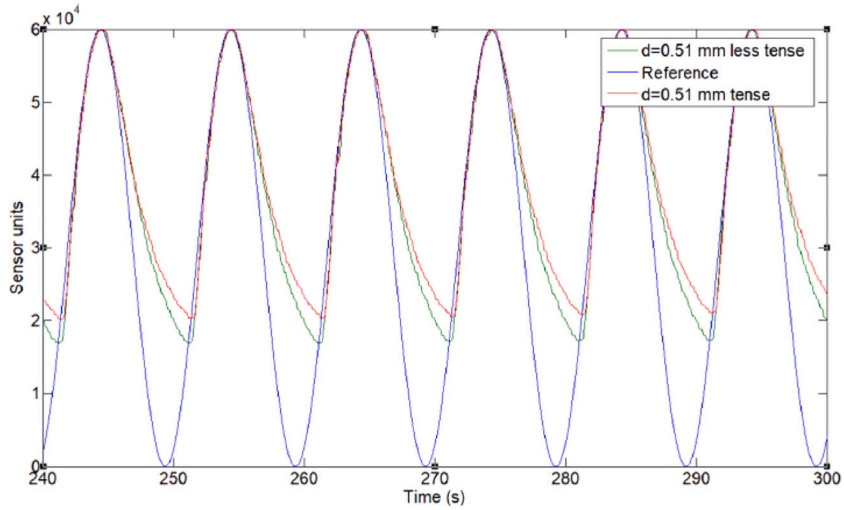

Fig. 9. Tensed vs less tensed single-wire SMA actuator.

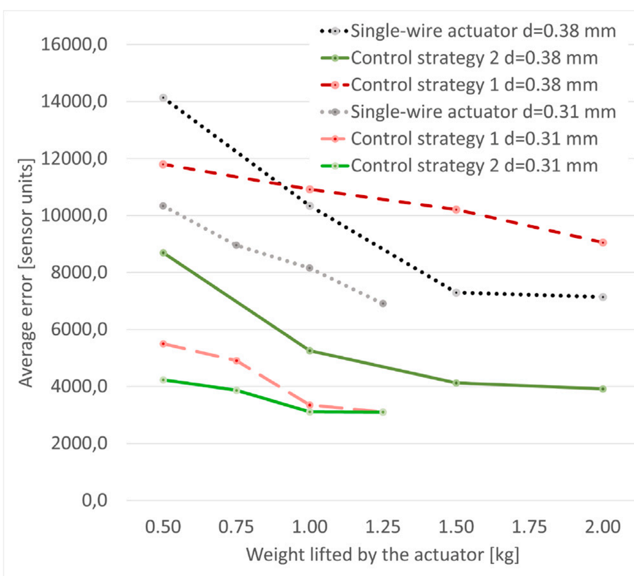

Fig. 10. Average error of different control strategies with different diameters and weights to be lifted (low activation temperature and 10 s period).

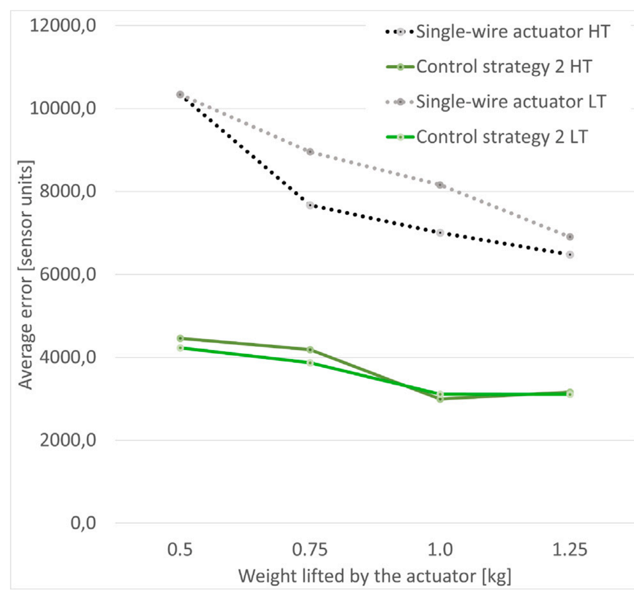

Fig. 11. Average error of different activation temperatures and weights to be lifted (0.31 mm diameter and 10 s period), single-wire actuator and Control strategy 2.

4.5. The effect of the activation temperature

The aim of this experiment is to evaluate the effect of the activation temperature. For this purpose, both versions of the 0.31 mm diameter wire (70 °C and 90 °C) will be compared. Once more, the weights to be tested are: 0.5 kg, 0.75 kg, 1 kg and 1.25 kg, and the: single-wire actuator and Control strategy 2.

Fig. 11 compares, for both 70 °C (LT) and 90 °C (HT) of activation temperature, the performance of a single-wire actuator (gray and black, respectively) and Control strategy 2 (light green and dark green, respectively) when lifting four different weights. This comparison is presented in terms of their average error with respect to the reference signal.

Fig. 11 shows that the high activation temperature version (90 °C) performs better than the low activation temperature one (70 °C) for the single-wire actuator. Notwithstanding, for Control strategy 2 this effect is not as pronounced. Once more, fluctuations are not very significant due to their reduced relative size.

4.6. The effect of frequency

Having proved that the performance of single-wire actuators can be improved by alternating their activation span, the next step is to check whether that result can be extrapolated to different frequencies or not. This time, a 0.31 mm diameter wire with an activation temperature of 90 °C and lifting 1.25 kg will be tested for six different periods of time: 6 s, 8 s, 9 s, 10 s, 12 s, and 15 s. These corresponding to 0.1667 Hz, 0.125 Hz, 0.1111 Hz, 0.1 Hz, 0.0833 Hz and 0.0667 Hz. Both the single-wire actuator and Configuration 2 will be compared with the reference signal.

It must be mentioned that, for this tests, Control strategy 2 was modified to deactivated when reaching 70% and the second wire is activated at 80% of the cycle duration. This change was made in order to correct the performance of the actuator since, during some tests, it showed a small delay when adjusting to the reference signal. Fig. 12 reflects the average error for both performances, a single-wire actuator (black) and Control strategy 2 (green), with respect to the given reference signal.

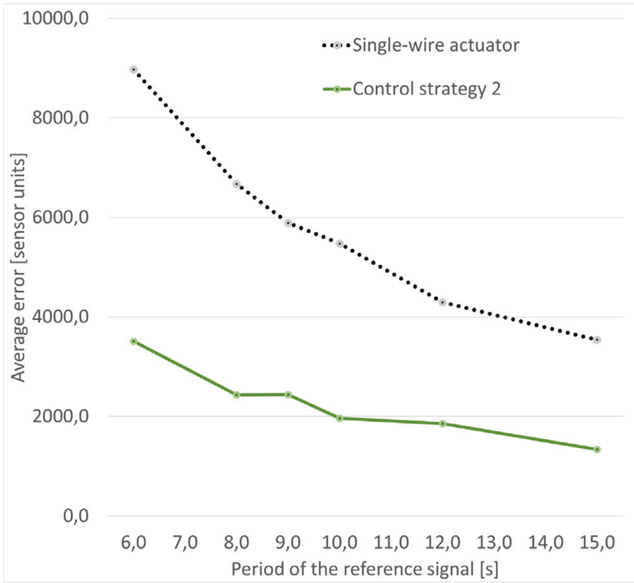

Fig. 12. Average error for different period cycles of their reference signal (0.31 mm diameter, Control strategy 2 and 0.125 kg of weight to be lifted).

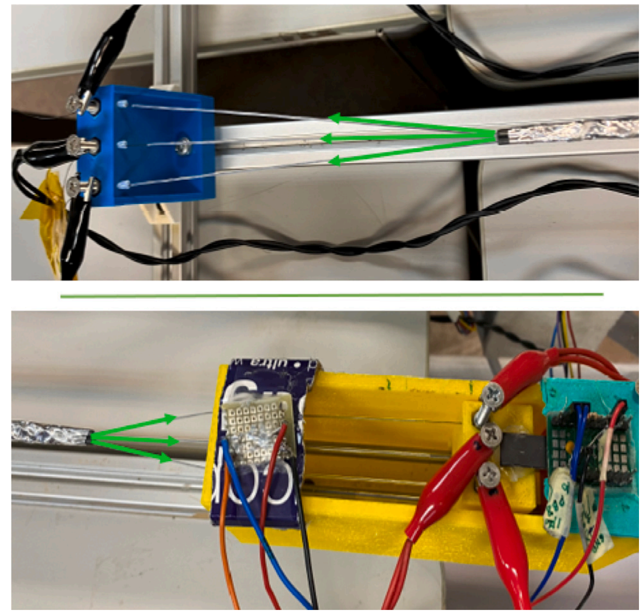

Fig. 13. Both fixed ends of the actuator.

Fig. 12 verifies that the solution found in this work can be applied adequately to different frequencies of the reference signal. With a 6-s-period reference signal, the actuator using Control strategy 2 performs appropriately for around 94% of the cycle while that percentage worsens to 85% when using the same wire all the time. (These 94% and 85% represent the percentage of the cycle where the actuator follows the reference accurately) Moreover, there is a clearly decaying tendency for the average error as the frequency decreases; this is due to the fact that, the longer the duration of the cycles, the more time the wires have to cool down even for the single-wire actuator. Naturally, the higher the frequency (the lower the reference signal period), the more noticeable is the improvement of using Control strategy 2 versus single-wire actuator.

4.7. The effect of geometry

Even though the asymmetrical configuration of the wires is initially overlooked, all through this subsection, its effect in the whole actuator behavior is analyzed. This asymmetrical configuration is observed in Fig. 13, where the green arrows evince the small angle created in between the fixed end points of the external wires with respect to the middle one and, hence, with respect to the actuation-axis of the multi-wire actuator.

This configuration angles are unavoidable in order to allow a proper fixing and powering of each wire (their ends must be separated from each other and electrically isolated) as Fig. 13 states. Thus, its effect in the whole actuator performance must be analyzed.

Fig. 14 shows how these small angles between the external wires and the middle wire (aligned with the axis of actuation of the multi-wire actuator) lead to a larger position error and worse results. This behavior is evidenced every two cycles (being coterminous with the middle wire activation), when the actuator shows a more accuracy response. To ease the lecture of this geometry effect, Fig. 14 presents the integral of the errors in a dark brown (middle wire activation) and a light brown (external wires activation) area. It is clear that the area between both curves is slightly smaller when the middle wire is activated when compared with the external wires. Nevertheless, this effect is not too marked and the final position error at the end of each cycle is stable. For these reasons, and after having analyzed the behavior of the asymmetrical wire configuration, the author has decided to dismiss its effect in the experimental results.

4.8. Antagonistic configuration

According to the results presented in this section, Control strategy 2 (one SMA wire per cycle) was chosen as multi-wire actuator in the antagonistic configuration. The test was driven over the rotating test bench shown in Fig. 2 – bottom. The control algorithm used with this configuration is based on the BPID controller presented in Section 3.1, with 6 independent controllers ($i = 6$). Each wire reference is generated according to the cycle and the actual position obtained from the angular position sensor. For this test, a 0.51 mm diameter SMA wire was used due to the test bench limitation. The pulley radio of the test bench is 45 mm which, along with the actuator force, produces a torque of 1.6 Nm on the joint. The test bench was configured with a payload of 0.5 kg at 200 mm which, at 90 degrees, generates a torque of approximately 1 Nm opposing to the actuator force.

In Fig. 15, the angular position response of the test bench in antagonistic configuration can be observed. Its response is generated by two single-wire actuators in antagonistic configuration, in such way that one actuator is activated in the flexion movement and another one is activated in the extension movement. The reference frequency is 0.051 Hz which means approximately one cycle every 20 s. According to Table 1, it would take 28 s for the configuration to work properly. Due this setup, the response of the actuator generates an error which increases over time (due to heat accumulation), forcing us to stop the system after 200 s (approximately 10 cycles of actuation) to avoid wires breaking.

The second test in antagonistic configuration, was done with multi-wire actuator with the Control strategy 2. A multi-wire actuator (3 wires) in the flexion movement and another multi-wire actuator (3 wires) on the extension movement; activating alternatively each actuator every cycle. The response of this test can be observed in Fig. 16 and can be compared with the response of the antagonistic configuration where single-wire actuator (only one wire per movement) is used (Fig. 15).

Using the multi-wire actuator in antagonistic configuration, the position error decreases when compared to single-wire actuator for each movement. Moreover, the period of continuous operation increases in more than 450 s (22 cycles), being able to keep working because errors in the actuators, and therefore heat, stabilizes (the position error does not increase significantly in time).

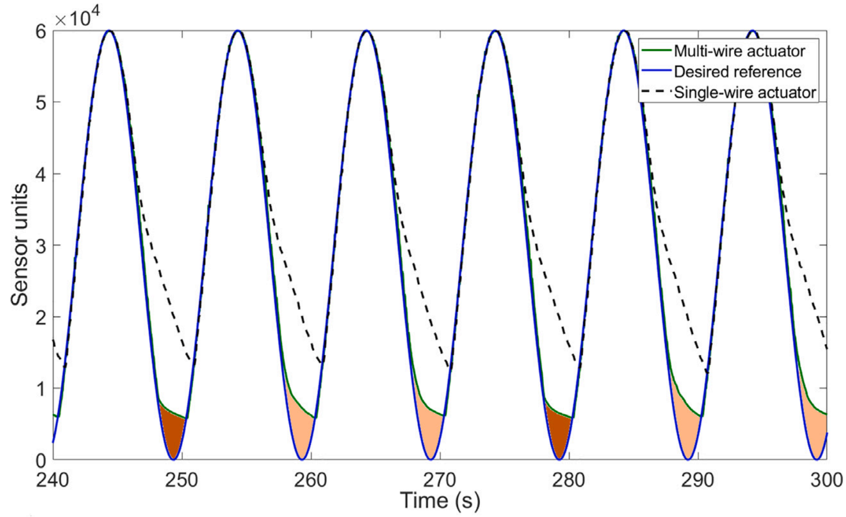

Fig. 14. Response signal of a single-wire actuator v.s Control strategy 2 (90 °C activation temperature, 0.31 mm diameter, 10 s period and 0.125 kg of weight).

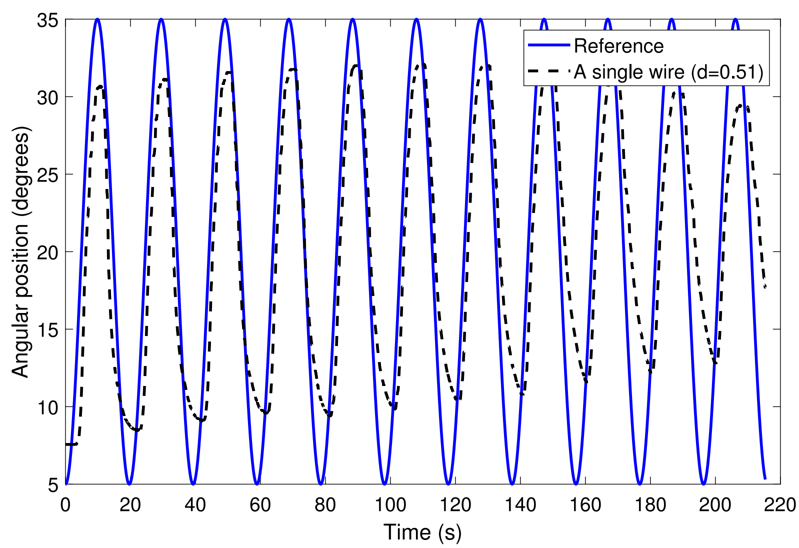

Fig. 15. Single-wire actuator response in antagonistic configuration.

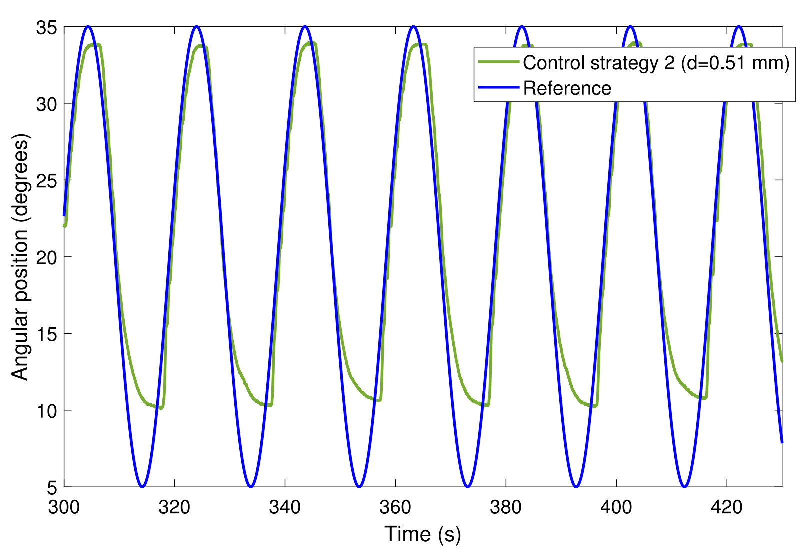

Fig. 16. Multi-wire actuator response in antagonistic configuration.

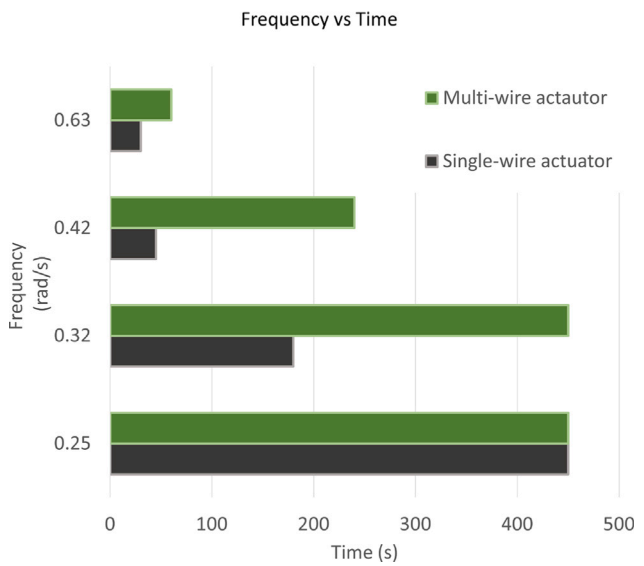

Fig. 17. Maximum working time achieved by each actuator (single-wire actuator v.s. multi-wire actuator) according to the frequency. After the maximum working time the system was stopped to avoid wires breakage, except the t = 450 seconds where the system can continue but the error is considered stable.

The asymmetry of the actuator response is due to the gravity force, and the test bench configuration. The first wire (agonist wire) lifts the weight opposing the gravity force and, therefore, requires higher temperatures in order to achieve the reference. The second wire (antagonist wire) shares direction with the gravity force, so it requires less temperature in order to follow the reference. Therefore, within the last part of the sinusoidal reference (around 35 degrees of the angular position) the agonist wire follows accurately the reference because the antagonist wire has cooled and regained its initial shape. In opposition, when the antagonist wire actuates (around 10 degrees) the agonist wire presents residual heat, so it is not capable to follow the reference.

These results show that, using a SMA multi-wire actuator with Control strategy 2, the performance of the system response has been greatly improved. Meanwhile, this fact opens up the possibility to actuate systems by SMA actuators at high frequency even though this operation is limited by the SMA cooling time. In Fig. 17 the maximum working time of the SMA actuators according to the different frequencies in antagonistic configuration is presented. The maximum working time was limited to 450 s, in this case the actuator could continue working, but it is considered a stable system. According to the results presented in Fig. 17, the continuous operation time of the multi-wire actuator increased substantially compared with the single-wire actuator, reaching more than twice as many cycles.

5. Discussion

Results prove that the multi-wire SMA actuator presents a better position response that the single-wire SMA actuator. Moreover, it can be stated that the performance of an actuator significantly improves by choosing:

- To alternate the use of several SMA wires: one wire per cycle, even actuating each one slightly in advance to the cycle where they primarily work. It is also important to leave some time between activations with no actuation.
- Weights or other recover mechanisms close to the maximum force that each wire can achieve.
- To reduce the effect of the geometrical disposition of the wires or to find a way of using them in order to improve the performance. The wires need to be as close to each other as possible in order to avoid the force decomposition.

Furthermore, frequencies of the reference signals used in testing are higher than the frequency recommended by the data-sheet. However, the above-mentioned conditions of a multi-wire actuator enable an improvement in performance while frequency increases when compared to a single-wire actuator.

These conditions share a common purpose: leaving the wire enough time to properly cool down an recover its initial shape. For this purpose, a combination of features have been used in order to grant the shortest cool down possible (a 0.31 mm diameter wire with a 90 °C activation temperature) and, additionally, a generous amount of time to do so.

By using more SMA wires for one actuator, performance improves as long as control and the actuator itself do not become too complex. Moreover, with the proposed actuator, developing a control algorithm that identifies the weight to be lifted and, automatically, establishes how many wires may be activated at the same time and their activation span will be extremely interesting and useful. For example, two wires can be activated at the same time if the actuator need to lift more weight. This adaptive actuator could be useful in many areas of engineering such as soft robotics, biomedical or aerospace.

In terms of energy consumption, the Control strategy 2 of the proposed multi-wire actuator (activating one wire each cycle) is similar to that one with just a wire working continuously.

The test bench was designed for only 3 wires, and it was not possible to test more than 3 wires. For more than 3 wires, the activation algorithm needs to be modified, but significant improvements are not expected. Multi-wire configuration gives more time to cool the wires and to not accumulate the heat in the Bowden cables, but the working frequency still depends on the cooling stage of each wire.

6. Conclusions

SMA-based actuators are an excellent choice due to their relatively low price, lightness and noiseless operation. However, as long as they are thermally activated, the recovery of their initial form upon cooling raises a drawback when high work frequencies are required. This study offers a solution to this problem by finding the combination of factors that leads to a better performance (SMA diameter and activation temperature) and by setting a configuration that uses three wires instead of one (multi-wire actuator) and two potential control strategies. The first one implied using two wires at the same time during the peak of the cycle of a sinusoidal reference signal and the second one used only one wire per cycle focusing on leaving the wires a rather long time to cool down. Tests were driven both on a linear test bench and in a rotative one for the antagonistic configurations measuring the position error of the actuator while following a given reference signal and lifting different sets of weights.

Results show that, the closer the weights to be lifted are to the maximum force supported by the wire, the better the wire recovers its initial shape. These results suggest that, in future applications, calculating the exact force needed to be support by the actuator is of the greatest importance. For instance, in exoskeletons actuation, joint-torque estimation will conform one of the most crucial steps, compromising the final efficient results. Additionally, it was found that using two wires at the same time, only improved the performance for thin wires and, since this work aimed to find a general solution, this activation strategy was discarded. However, this configuration may be considered for miniaturized applications, where both actuators and the forces beared by them have smaller requirements.

On the other hand, the second control strategy (using one wire per cycle) satisfactorily proved to enhance the performance of the multi-wire actuator with respect to the single-wire actuator, regardless of the rest of conditions. Moreover, the less convenient the circumstances are (high frequency, small weight, and thicker wire), the more the improvement can be noticed. Furthermore, over-dimensioning the actuator and working between 0.8% and 3.8% of SMA strain has been proven to minimize the position error when the actuator works at high frequencies. This control strategy greatly improved the performance of the system response as well for the antagonistic configuration, used in rotations, being able to work at a higher frequency, during more cycles continuously and to considerably reduce the position error. These results are inspiring for their future application as a soft actuator for rehabilitation exoskeletons, where antagonistic configurations are broadly extended. Moreover, low frequency presented the main drawback for SMA actuators in these type of applications; enhancing this parameter may open the door for its use in future applications.

To sum up, this work has proved to enhance the frequency performance of SMA actuators by combining them in a multi-actuator configuration. Moreover, it provides inspiring results in the use of SMA as soft actuators for exosuits as long as their low price, size and weight properties, combined with this improvement in their frequency performance, turn them into a suitable and accurate material for this purpose. Moreover, this frequency improvement has been achieved without the necessity of an external device which may increase the size, price, weight and complexity of the actuator nor the need of higher energy requirements; making a great difference with previous results found in the literature.

CRediT authorship contribution statement

Janeth Arias Guadalupe: Developed the control strategy, Performed the laboratory tests, Analyzed the results, Helped with the manuscript writing. **Dorin Copaci:** Helped on the control strategy algorithm development and actuator development, Wrote the manuscript. **Paloma Mansilla Navarro:** Collaborated on the laboratory tests, Helped to write the manuscript. **Luis Moreno:** Project administration, Funding acquisition, Collaborate on the actuator design and control strategy. **Dolores Blanco:** Project administration, Funding acquisition, Collaborated in writing the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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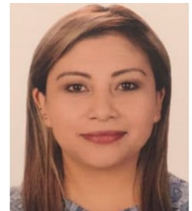

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