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Khan, Muhammad Amir Hamza; Manfredi, Luigi; Velsink, Florien; Huan, Yu; Cuschieri, Alfred

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Analysis of performance and energy efficiency of thin shape memory alloy wire-based actuators.

H. Khan, L. Manfredi, Y. Huan, F. L. Velsink, A. Cuschieri
The Institute for Medical Science and Technology, University of Dundee, Dundee, UK

Abstract:
Recently actuators based on smart materials have attracted considerable interest in the field of Microelectromechanical systems (MEMS), due to their potential to provide high power-to-weight ratio. Shape memory alloy (SMA) s are effective these material for actuation because of their lightweight, low power consumption, and heating actuated and superelastic properties. The objective of the current study concerns the selection of the appropriate design configuration for thin SMA wire-based actuators. We proposed two compact SMA-wire based rotary actuators, which use thin SMA wires or extension spring in antagonist configuration. The main contributions of this paper are the study of position tracking performance of the proposed actuators on a purpose designed reconfigurable experimental test bed as a proof-of-concept together with evaluation of their energy efficiency.

Keywords: Smart materials, SMA Actuators, SMA wires

Introduction

In recent years, the active materials [4,7, 9] have provided an effective solution for the design compact and high performance actuators for the miniaturized robotic applications. Shape memory alloys (SMAs) are uniquely suited to miniaturization with the added benefit of low power consumption. SMAs as straight-wires are most commonly used in SMA actuator systems [15], these wires contract when it is heated, and revert to their original length on cooling it [10, 16]. The heating of SMA wires is easily achieved by changing their electrical resistance. However, one of the main challenges of SMA actuators concerns achieving a high bandwidth. Thus, a maximum bandwidth of 0.033-2 Hz is reported in the published literature [13]. Moreover, the maximum achievable bandwidth of SMA based actuators is highly dependent on the efficiency of the method used for cooling the wires [3]. The actuation frequency can be increased by rapid cooling of the SMA wire, usually by forced heat convection. *Wet SMA actuators* [8, 12, and 14] are characterized by an SMA wire embedded within a compliant electrolyte fluid-filled tube, an arrangement that allows electricity to be used for heating the wire, causing its contraction. In this arrangement, cold fluid is pumped through the tube for fast cooling of the wire, resulting in relaxation (extension). However, this arrangement increases the overall mass of the system and requires more heat to contract the SMA. The wet SMA actuators power-to-weight ratio is typically smaller. Another important factor in the achieving the desired bandwidth with SMA wire is its thickness. Currently, the thinnest SMA wires readily available in the market are 25 μm diameter. These SMA wires have low cooling time (up to 0.15 Sec) [1] with faster cooling at room temperature. The higher bandwidth comes at the expense of a lower output force. For the SMA wire to return to its original state after cooling, a bias force is needed. The application of this bias force and pre-stress on the wires also influence the bandwidth of the actuator. The bias force can be passive, by a spring or mass. An antagonistic configuration of SMA wires can also be used, in which arrangement; the other SMA wire undergoes the reverse transformation. As the bias force is not constant, it influences the bandwidth. [13].

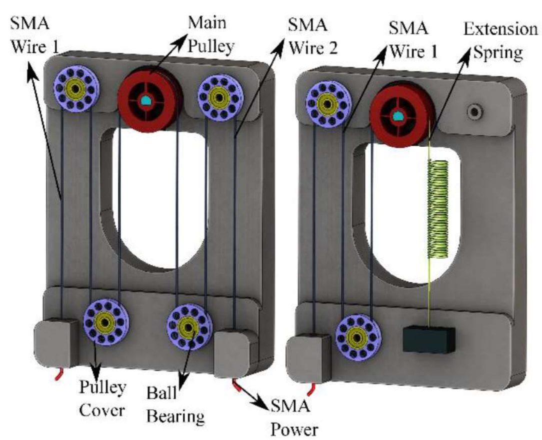

Fig. 1: *The proposed SMA-wire based actuators design, these actuators provide rotary actuation through an output shaft attached with a main pulley (in red);* ***Left:*** *SMA wire Vs SMA wire.* ***Right:*** *SMA wire Vs linear spring.*

Recent advancements in thin SMA wires have enabled their use for compact and high performance actuators for the low actuation force applications. Novel actuators have been developed, using many different configurations of SMA wires, such as miniature rotational actuators. [17], [11] Practical applications include a walking hexapod micro-robot [6], a prosthetic hand [2], a flexible smart needle and robotic surgery i.e. active snake like endoscope or colonoscope.

In the present paper, we propose the design of two compact SMA-wire based actuators (Fig. 1). We designed and fabricated a reconfigurable experimental test bed (see in Fig. 7) and used it to test their performance in a proof-of-concept study on their energy efficiency.

Methods

We studied the actuation of two configurations of SMA wire-based actuators, the shown in Fig. 1. **Actuator design 1**: this has 2 *SMA wires in antagonistic configuration* (Fig. 1 ***Left***). Its working principle is demonstrated in Fig. 2, with the motion being transmitted to a main pulley (in black) by the two SMA wires connected to it and is electrically ground (circled in yellow). The pulley can rotate clockwise or anticlockwise, depending on extension and contraction of the opposing SMA wires. Fig. 2 ***Left*** shows that SMA wire 1 (S1) is fully contracted when SMA wire 2 (S2) is fully extended; in Fig. 2 ***center*** both SMA wires are Semi-contracted which allows a main pulley at half way of its full range of angle θ.

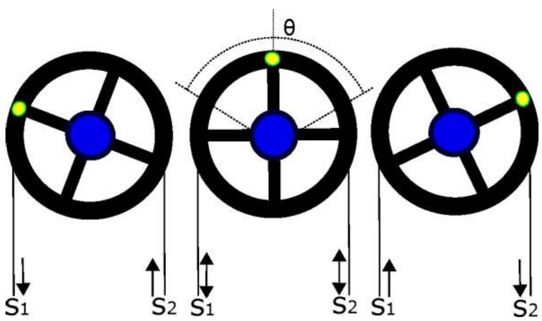

Fig. 2: *The demonstration of SMA wire VS SMA wire actuator movement.* ***Left****: when SMA wire 1 (S1) is fully contracted and SMA wire 2 (S2) is fully extended* ***Center:*** *when both SMA wires are semi-contracted.* ***Right:*** *when S2 is fully contracted and S1 is fully extended.*

Similarly, when S2 is contracted fully and as a result S1 is extended to it full length, the main pulley reaches the limit of the right side (Fig. 2 ***right***).

In actuator design 2 the *SMA wire acts against q linear spring*: here the rotation motion of a main pulley is generated by SMA wire with the extension spring being connected to it in antagonist configuration. As can be seen in Fig. 1 ***right***; the extension spring stores the mechanical energy when SMA wire is active and it releases stored energy when SMA wire is lengthens with cooling. As a result, a main pulley rotates clockwise or anticlockwise. In the design, the small pulleys are used to accommodate SMA wire on each side, thereby reducing the size of actuator. Each small pulley incorporates of ball bearing and pulley cover, designed to minimize the contact surface and hence reduce friction between SMA wire and its pulley cover. In these proposed actuators design, the ball bearings are used primarily to reduce friction and increase the efficiency of the system. These actuators are designed by using the Dynalloy Flexinol's [1] nickel titanium (NiTi) alloy wires in straight form, which can be contracted by 5% of their total length. In these actuators, the total length of the SMA wire L is estimated by using the outer radius of the pullet r and desired total range of rotation angle θ for actuator.

Each side total SMA wire length is defined as

$$L = \frac{r\theta}{0.05} \qquad (1)$$

A total SMA wire length is attached to main pulley is directly proportional to its total range of rotation motion and outer radius. It can be seen from Fig. 3, the total of each SMA wire length L for the different main pulley sizes (outer radius r 1 to 3) and different colour lines represent the different total range of rotation angles.

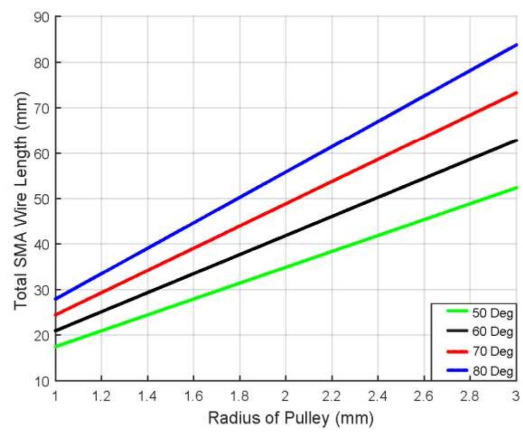

Fig. 3: *The estimated total SMA wire length (mm) for the different main pulley sizes (outer radius) and its total range of rotation angle (Deg).*

To investigate these SMA-wire based actuator configurations in detail, we designed a reconfigurable experimental test bed, which can adjust different sized pulleys and lengths of SMA wires (described in next Section).

Experimental Setup

As a proof-of-concept, the performance and energy efficiency analysis for the proposed rotary actuators were assessed on a purpose designed test bed as shown in Fig. 4. Its design can form both configurations. In addition, the test bed can accommodate different sizes of a main pulley (configurable up to 7.5 mm outer diameter) and different length SMA (up to 85 mm length on either side).

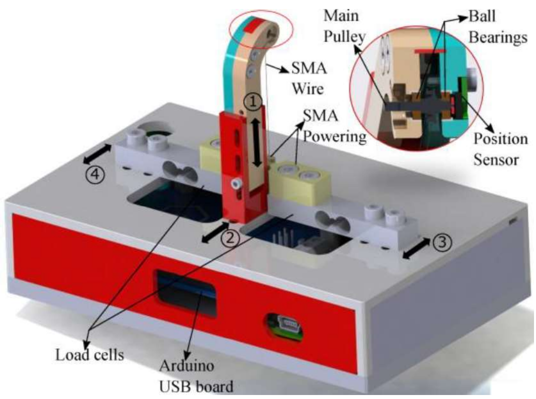

Fig. 4: *The CAD of the experimental test bed;* ***Red encircled view:*** *A main pulley's cross-section view.*

A main pulley is fitted in between two ball bearings, which are pressed fitted into two separate supporting links attached together with screws to make one unit. This unit can move up and down as indicated by black arrow 1 in Fig. 4. This adjustable one degree of freedom allows the test rig to accommodate 30mm to 85 mm long SMA wires on either side. One end of each SMA wire is connected to a main pulley, which is electrically grounded and other end is attached to powering base connector. Each side of the SMA wire-powering base is locked on a load cell used for sensing tension force in each wire or spring and is able to measure up-to 780 g force. The distance between these load cells is configurable as shown by black arrows 3 and 4 in Fig.4, needed to accommodate different sizes of the main pulleys. A position sensor is integrated into one side of supporting link (it can be seen in red encircled view in Fig.4). It measures the rotation of a main pulley. The 1 resistive current sensors (measure up to 1 A current) are used to assess power consumption for each SMA wire. The Arduino USB board is placed in the lower chamber of this test bed. It works as bridgeboard and connects to the computer with a standard USB cable and it gets reading from the joint position sensor, two current sensors and two load cells. The PC also sends control pulse width modulation (PWM) input for each SMA wire.

Experimental Results

The experiments are performed by using close loop PID position controller for a 1 Hz sine position reference. In order to keep the desired position, the PID controller sends two separate PWM input for each side SMA wires in Actuator 1 (SMA wire Vs. SMA wire) configuration and one PID position control input for only SMA wire in actuator 2 (SMA wire Vs. linear spring).

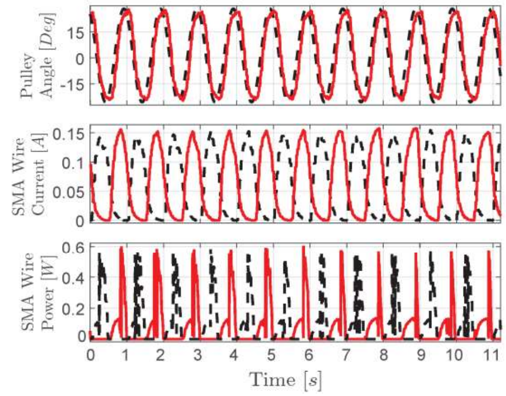

Fig. 5: *The results of Actuator 1 (SMA wire Vs SMA wire actuator) configuration for a 1 Hz sine position reference;* ***(top):*** *Position tracking of a main pulley, where a black dashed indicates the reference position and red solid line the actual position;* ***(middle):*** *Current for SMA wire 1 (red solid line) and SMA wire 2 (black dashed);* ***(bottom):*** *Power.*

The diameter of 76µm SMA wires and spring of stiffness 0.18 N/mm were used in these experiments. The position tracking and power consumption can be seen in Fig. 5 for SMA wire vs. SMA wire actuator, whereas the single SMA wire power shown in Fig. 6 for SMA wire vs linear spring. These results confirmed the precise position tracking for both actuators, but active phase SMA wire against spring consumed more power to overcome initial spring force.

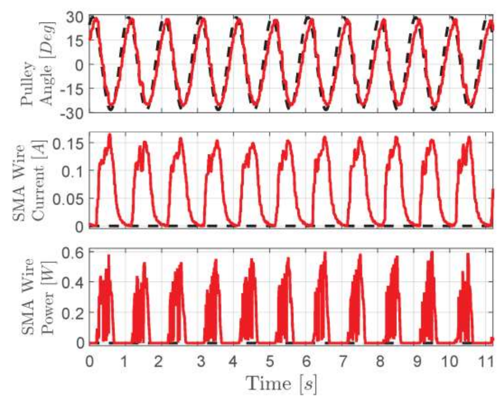

Fig. 6: *The results of Actuator 2 (SMA wire vs Spring actuator) configuration for a 1 Hz sine position reference;* ***(top):*** *Position tracking of a main pulley, where a black dashed indicates the reference position and red solid line the actual position;* ***(middle):*** *Current for SMA wire in red solid line;* ***(bottom):*** *Power consumption.*

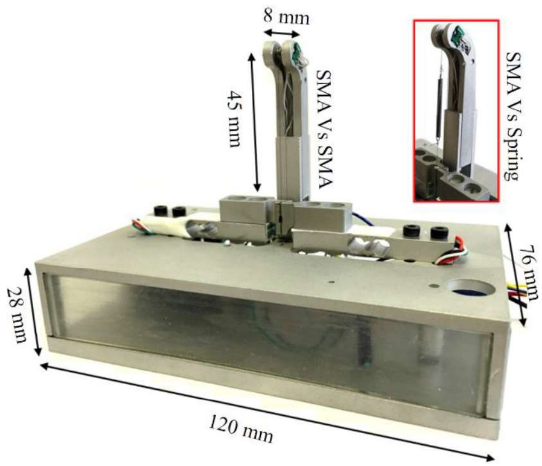

Fig. 7: *The picture of experimental test bed with SMA wire VS SMA wire configuration installed on it;* ***(top right in red*** *:) SMA wire VS Spring configuration.*

Conclusion

The aim of this work is to facilitate the designers to select appropriate configuration for thin SMA wire-based actuators. We proposed two SMA-wire based actuators design as shown in Fig. 1. For a proof-of-concept, the reconfigurable experimental test bed is designed and constructed (see in Fig. 7). The actuation performance is tested on it for both actuators under no external loading and position is tracked for a 1 Hz sine position reference. In the results, it is shown that an active phase of SMA wire in antagonist configuration against spring consume more power than non-active or semi SMA wire. However, both configurations achieved precise position tracking with selection of an appropriate extension spring. ***Future Work:*** The future work will be the testing of both proposed actuators under different external loading and their performance will be analysed using force feedback.

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