PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

A torsional artificial muscle from twisted nitinol microwire

Seyed M. Mirvakili, Ian W. Hunter

Seyed M. Mirvakili, Ian W. Hunter, "A torsional artificial muscle from twisted nitinol microwire," Proc. SPIE 10163, Electroactive Polymer Actuators and Devices (EAPAD) 2017, 101630S (17 April 2017); doi: 10.1117/12.2261712

Event: SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring, 2017, Portland, Oregon, United States

A torsional artificial muscle from twisted nitinol microwire

Seyed M. Mirvakili[*], Ian W. Hunter

Department of Mechanical Engineering, BioInstrumentation Laboratory, Massachusetts Institute of Technology, Cambridge, MA, 02139, USA.

ABSTRACT

Nitinol microwires of 25 µm in diameter can have tensile actuation of up to 4.5% in less than 100 ms. A work density of up to 480 MPa can be achieved from these microwires. In the present work, we are showing that by twisting the microwires in form of closed-loop two-ply yarn we can create a torsional actuator. We achieved a revisable torsional stroke of 46 °/mm with peak rotational speed of up to 10,000 rpm. We measured a gravimetric torque of up to 28.5 N·m/kg which is higher than the 3 – 6 N·m/kg for direct-drive commercial electric motors. These remarkable performance results are comparable to those of guest-infiltrated carbon nanotube twisted yarns.

Keywords: Torsional Artificial Muscle, Shape Memory Alloy, Nitinol, Twisted Fiber.

1. INTRODUCTION AND BACKGROUND

Since the discovery of the shape-memory effect in 1930s many devices have been made that exploit this remarkable effect including torsional actuators. By twisting a 100 µm nitinol wire (NiTi alloy) and differentially heating it along its length, Walker *et al.* at AT&T Bell Laboratories showed that torsional actuation can be observed [1]. The working principle relies on the shape recovery of the twisted wire. In their design, half of the length of the nitinol wire was Joule heated via an electrical contact in the middle. This three-contact configuration limits the practicality of such torsional actuator. In the present work, we introduce an alternative design in which the torsional actuator works without any need for the middle electrical contact.

The recent advancements in fabrication of shape memory alloy wires have reduced the diameter of nitinol wires down to 25 µm. The smaller diameter wires cool more rapidly which enables

---

[*] seyed@mit.edu, BioInstrumentation Laboratory, Massachusetts Institute of Technology.

Electroactive Polymer Actuators and Devices (EAPAD) 2017, edited by Yoseph Bar-Cohen, Proc. of SPIE
Vol. 10163, 101630S · © 2017 SPIE · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2261712

a higher cycling rate. Although there are techniques to reduce the cooling time [2], [3], for simplicity we used 25 µm nitinol wires in the present work.

Other types of miniature torsional actuators made from infiltrated (guest) carbon nanotube or niobium nanowire yarns are shown to produce remarkable torsional stroke (up to 16 °/mm), rotational speed (up to 11,500 rpm), and gravimetric torque (up to 8 N·m/kg) [4]–[7]. The mechanism by which these nanofiber-based torsional actuators work is based on the volumetric expansion of their stimuli-responsive guest material. Here, by using only one length of nitinol microwire we achieved performance results which favorably compare to those of nanofiber-based torsional actuators. The key working mechanism here is shape recovery of the twisted nitinol wire via Joule heating.

2. METHODS

The torsional actuator is made of one length of nitinol microwire (25 µm in diameter) with two ends connected to electrical contacts to one side of the device (figure 1 A). By attaching a loop to middle of the microwire and twisting it, we formed a twisted structure illustrated in figure 1A. The other side of the loop is attached to a load (figure 1A). To observe the torsional actuation, we attached a small paddle (4 mm × 10 mm × 25 µm) made of a piece of aluminum foil close to the junction where two microwires meet (figure 1A). We used a programmable power supply (Agilent B2962A) to excite the actuator with voltage pulses of different width and amplitude. To measure the torsional speed and stroke, we used a high-speed camera (1,000 fps, SAMSUNG TL350). An algorithm was implemented in MATLAB to extract the data from the high-speed video files.

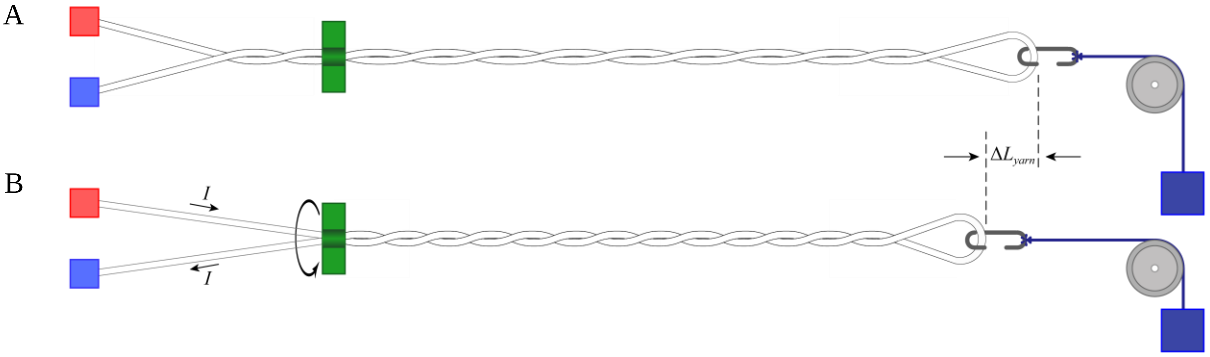

Figure 1 – (A) An illustration of the actuator structure and its working cycle. The components are not to scale. (B) By passing current through the nitinol microwires we achieved torsional actuation.

The maximum generated torque from this structure can be estimated from the maximum torsional stroke (θ_m) and the torsional spring constant of the yarn (κ) by using $\tau_m = \kappa\theta_m$. By applying square wave input signal, with appropriate width and amplitude, the paddle oscillates at the resonance frequency of the structure when it reaches the peak torsional stroke. By measuring this resonance frequency and using the moment of inertia of the paddle ($I = m(l^2 + w^2)/12$) we can estimate the torsional spring constant from $\kappa = I\omega_n^2$. The specific work capacity, a measure of how much work a torsional actuator can output, can be estimated from the maximum torque and torsional stroke ($W_m = \tau_m\theta_m / 4$).

3. RESULTS AND DISCUSSION

We measured peak speed of almost 10,000 rpm with torsional stroke of up to 46 °/mm (Figure 2). The peak speed is lower than the 11,500 rpm from wax-infiltrated multi-walled carbon nanotube yarns [4] but higher than the 7,200 rpm for wax-infiltrated niobium nanowire yarns [6]. The torsional stroke is higher than the 0.6 °/mm for NiTi monofilament torsional actuators [1] and the 16 °/mm for MWCNT wax-infiltrated yarns [4].

We measured gravimetric torque of up 28 N·m/kg which is higher than the reported values for MWCNT and niobium nanowire wax-infiltrated yarns. This remarkable gravimetric torque is also higher than the 3 – 6 N·m/kg for ungeared direct-drive commercial electric motors.

By twisting the looped nitinol wire from its middle, since the two ends of the wire are clamped, the entire length of the wire twists. Therefore, the two segments of the wire between the electrical contacts and the junction where they meet will also have twist on them (figure 1B). By applying current, these two segments untwist and make the section between the junction and the paddle to untwist. As the two segments untwist the junction moves towards the paddle and therefore, length of each segment increases (figure 4). As the section on the left side of the paddle is untwisting, the rest of the yarn twists until it counterbalances the torque generated by the torsional stroke. The stored energy in the twisted part rotates the paddle back to its initial angular position when the voltage is turned off. The number of unwinding rotations depends on the initial inserted twist and length of the microwire.

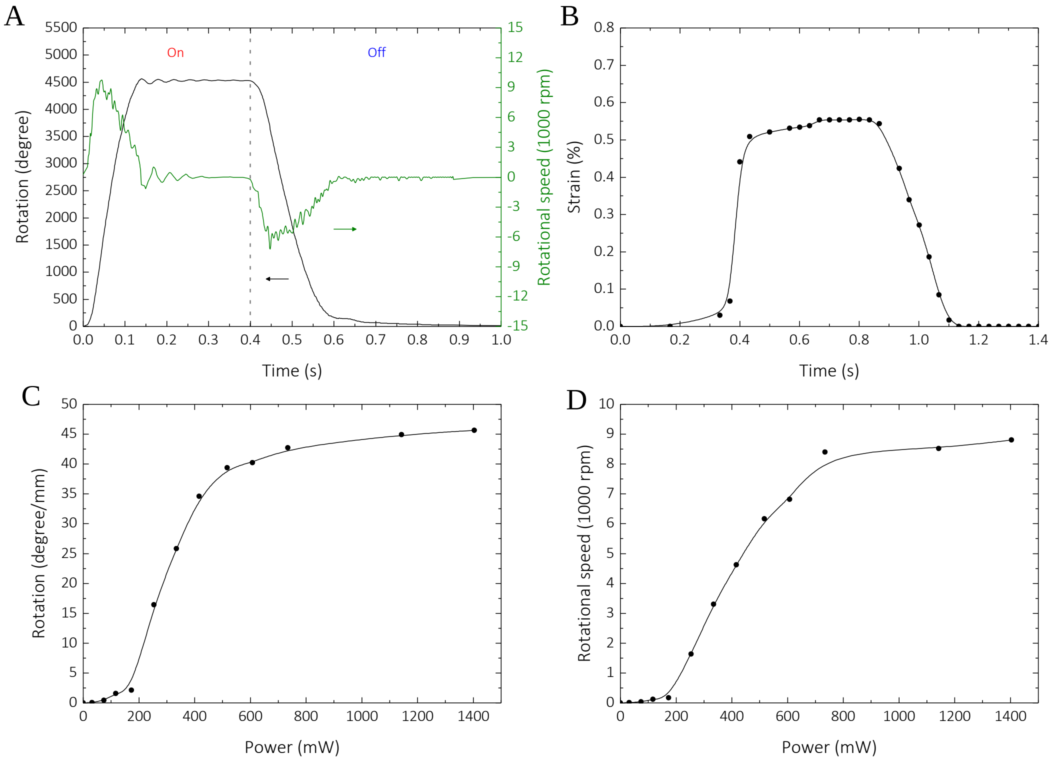

Figure 2 – (A) Response of the actuator to a square wave input with amplitude of 14 V and width of 400 ms (1.4 W). The sample had an initial inserted twist number of 75 with initial length of 250 mm. Sample was under a load of 24 MPa. (B) Tensile actuation of the actuator in (A) with the same input power. (C) Normalized torsional stroke of the actuator as a function of input power. (D) rotational speed of the actuator as a function of input power.

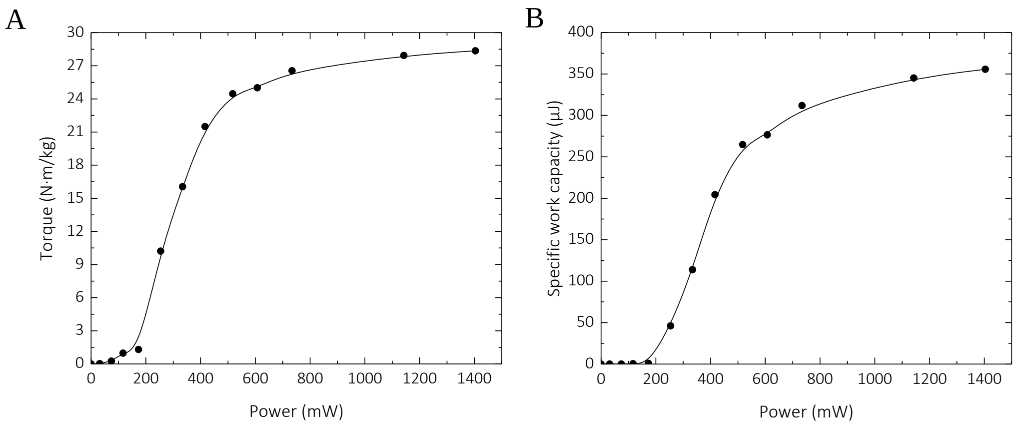

Figure 3 – (A) Gravimetric torque of the actuator as a function of input power. (B) Specific work capacity of the actuator as a function of input power (mass of the yarn is 0.63 mg).

Due to the twisting/untwisting of different sections of the wire, we expect to see a linear stroke as well. This linear actuation is due to two separate phenomena: 1) shape recovery of the Joule heated sections of the wire which untwists the sections on the left side of the paddle; 2) change in length due to an increase in the number of twists for the section on the right side of the paddle. We derived an equation that predicts the linear stroke in the yarn from some of the measurable parameters. Figure 4 illustrates the diagram we have used to derive the equation. As illustrated here, when the yarn untwists the length of the wires between the electrical contact and the junction (noted as l_o and l) increases. However, the length of the twisted pair (noted as h_o and h) decreases because of the increase in the inserted twist (noted as n_o and n).

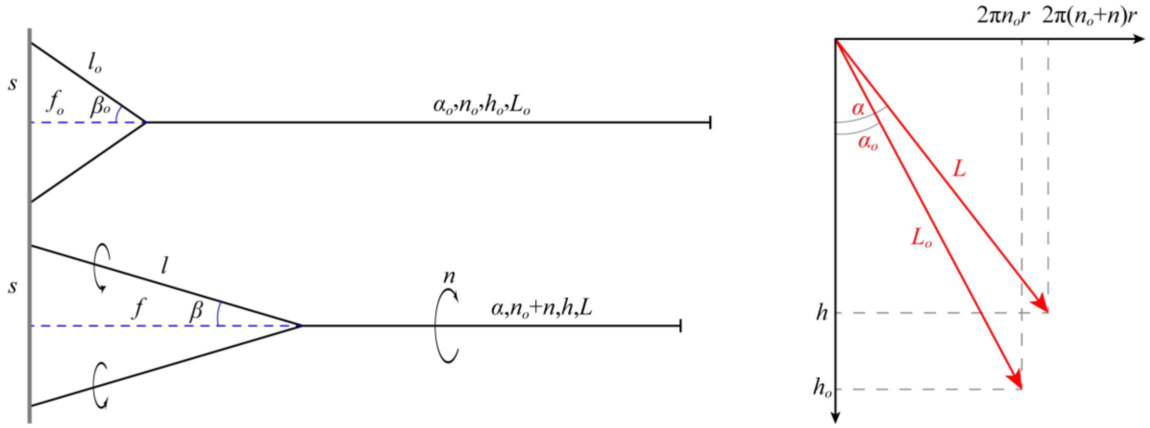

Figure 4 – Top and bottom left: illustrates the actuation mechanism and changes in the inserted twist and length of the actuator. Right: illustrates the geometry of a helix and its relationship with the length and the number of twists.

Using the helix geometry and trigonometric functions, we find the ΔL_{yarn} (figure 1) to be:

$$\Delta L_{yarn} = l\cos(\beta) - l_o\cos(\beta_o) + h - h_o, \qquad (1)$$

where the Δh can be measured directly from the experiment or we can find it from the following equation:

$$\Delta h = \frac{(n+n_o)\pi D}{\tan(\alpha)} - \frac{n_o \pi D}{\tan(\alpha_o)}. \qquad (2)$$

We know that $\Delta l = n\pi D/\sin(\alpha_o) - \delta l$, where δl is the change in length of the microwire segments between the electrical contacts and the junction due to the phase transition [2]. The change in total length of one of the microwires (i.e., $L+l$) is:

$$L_o - L = \Delta l = \frac{n\pi D}{\sin(\alpha_o)} - \delta l\,. \tag{3}$$

Therefore, $\Delta L = - n\pi D/\sin(\alpha_o) + \delta l$ which is equal to:

$$\Delta L = -\frac{n\pi D}{\sin(\alpha_o)} + \delta l = \frac{(n_o + n)\pi D}{\sin(\alpha)} - \frac{n_o \pi D}{\sin(\alpha_o)}\,. \tag{4}$$

We can assume that at rest (i.e., before excitation) the twist angle in the yarn (α_o) is equal to β_o. Therefore, the twist angle in activated state, α, is:

$$\alpha = \sin^{-1}\left(\frac{\sin(\beta_o)(n_o + n)\pi D}{\delta l \sin(\beta_o) + (n_o - n)\pi D}\right). \tag{5}$$

Now, we can rewrite the equation 1 as:

$$\Delta L_{yarn} = s\big(\cot(\beta) - \cot(\beta_o)\big) + \cot(\alpha)(n + n_o)\pi D - \cot(\beta_o) n_o \pi D\,. \tag{6}$$

From equation 6, we can conclude that the distance between the electrical contacts ($2s$) and the number of inserted twists (n) have a direct impact on the linear actuation. This conclusion agrees with our observation from the experiments.

We measured linear stroke of 0.55% for a yarn with 75 inserted twists with final length (h_o+f_o) of 100 mm (figure 2B). The separation between the electrical contacts was 30 mm.

4. CONCLUSION

In conclusion, in this work we presented a simple method for fabricating a large stroke torsional actuator with a single nitinol microwire without using a third contact. The very small linear actuation in the yarn enables us to use this actuator in devices where the length should be constant and only torsional stroke is desirable. Although shape memory alloys have shorter cycle life compared to CNT yarns, their abundancy and ease of handling make them very comparable to nanofiber-based torsional actuator from system point of view.

5. ACKNOWLEDGMENT

S.M.M. was supported by a Natural Sciences and Engineering Research Council of Canada (NSERC) Alexander Graham Bell Graduate Fellowship. S.M.M. would also like to acknowledge earlier discussions with Professor John D. Madden of University of British Columbia.

References:

[1] Gabriel, K. J., Trimmer, W. S. N. and Walker, J. A., "A micro rotary actuator using shape memory alloys," Sens. Actuators 15(1), 95–102 (1988).

[2] Hunter, I. W., Lafontaine, S., Hollerbach, J. M., and Hunter, P. J., "Fast reversible NiTi fibers for use in microrobotics," in Proceedings. IEEE Micro Electro Mechanical Systems, 166–170 (1991).

[3] Hunter, I., and Lafontaine, S. R., "Shape memory alloy fibers having rapid twitch response," US5092901 A, (1992).

[4] Lima, M.D., Li, N., De Andrade, M.J., Fang, S., Oh, J., Spinks, G.M., Kozlov, M.E., Haines, C.S., Suh, D., Foroughi, J. and Kim, S.J., "Electrically, chemically, and photonically powered torsional and tensile actuation of hybrid carbon nanotube yarn muscles," Science, 338(6109), 928-932 (2012).

[5] Lima, M.D., Hussain, M.W., Spinks, G.M., Naficy, S., Hagenasr, D., Bykova, J.S., Tolly, D. and Baughman, R.H., "Efficient, Absorption-Powered Artificial Muscles Based on Carbon Nanotube Hybrid Yarns," Small, 11(26), 3113-3118 (2015).

[6] Mirvakili, S.M., Pazukha, A., Sikkema, W., Sinclair, C.W., Spinks, G.M., Baughman, R.H. and Madden, J.D., "Niobium nanowire yarns and their application as artificial muscles," Advanced Functional Materials, 23(35), 4311-4316 (2013).

[7] Chun, K.Y., Kim, S.H., Shin, M.K., Kwon, C.H., Park, J., Kim, Y.T., Spinks, G.M., Lima, M.D., Haines, C.S., Baughman, R.H. and Kim, S.J., "Hybrid carbon nanotube yarn artificial muscle inspired by spider dragline silk," Nature communications, 5, (2014).