Development of a SMA-Fishing-Line-McKibben Bending Actuator

CHAOQUN XIANG[ID]**1, JIANGLONG GUO**[ID]**1, YANG CHEN**2**, LINA HAO**2**, (Member, IEEE), AND STEVE DAVIS**3

[1]Bristol Robotics Laboratory, Soft Robotics Group, University of Bristol, Bristol BS16 1QY, U.K.
[2]School of Mechanical Engineering and Automation, Northeastern University, Shenyang 110819, China
[3]Centre for Autonomous Systems and Advanced Robotics, University of Salford, Salford M5 4WT, U.K.

Corresponding author: Lina Hao (haolina@me.neu.edu.cn)

ABSTRACT High power-to-weight ratio soft artificial muscles are of overarching importance to enable inherently safer solutions to human–robot interaction. Traditional air-driven soft McKibben artificial muscles are linear actuators, and it is impossible for them to realize bending motions through use of a single muscle. More than two McKibben muscles are normally used to achieve bending or rotational motions, leading to heavier and larger systems. In addition, air-driven McKibben muscles are highly nonlinear in nature, making them difficult to be controlled precisely. An shape memory alloy (SMA)-fishing-line-McKibben (SFLM) bending actuator has been developed. This novel artificial actuator, made of an SMA-fishing-line muscle and a McKibben muscle, was able to produce the maximum output force of 3.0 N and the maximum bending angle (the rotation of the end face) of 61°. This may promote the application of individual McKibben muscles or SMA-fishing-line muscles alone. An output force control method for the SFLM is proposed, and based on MATLAB/Simulink software, an experiment platform is set up and the effectiveness of control system is verified through output force experiments. A three-fingered SFLM gripper driven by three SFLMs has been designed for a case study and for which the maximum carrying capacity is 650.4 ± 0.2 g.

INDEX TERMS Expansive McKibben muscle, fishing line, SMA-fishing-line, SMA-fishing-line-McKibben actuator, force control.

I. INTRODUCTION

Traditional robotic systems have been driven by rigid actuating systems such as motors and hydraulic actuators, which usually require complex gear transmission systems or reducers and heavy hydraulic actuating cylinders, leading to robotic systems that are bulky, inflexible, and intrinsically unsafe when interacting with human beings [1]. Soft robots are bio-inspired and versatile soft machines that are poised to revolutionize the role of robotics in various robotic applications such as pick-and-place of delicate objects. They are usually driven by cables [2], [3] and soft actuators that are lightweight, have high power density, are flexible, and inherently safe [4]. Artificial muscle actuators (AMAs) are the most popular soft actuators. AMAs include electroactive polymer actuators [5]–[7], shape memory alloy/polymer actuators [8], fishing line actuators [9], and pneumatic actuators [10], [11].

Shape memory alloy (SMA) wires are usually made of titanium alloy metal wires. Their displacements can be controlled by relatively low voltage electrical heating. After cooling, they can move back to their original states. SMAs are lightweight and have relatively high power-to-weight ratios. They have been, therefore, extensively employed for robotic grippers and manipulators [12]–[14]. They are, however, slow in response (low bandwidth) as the cooling time is relatively long. In order to accelerate their response speeds, additional cooling devices and delicate control methods are usually needed. In addition, the maximum contraction of SMA wires is only 4% of their original lengths [15].

Fishing line actuators, firstly designed by Haines *et al.* [9], were made of low cost twisted polyethylene and nylon polymer fibers. The movement of fishing line actuators can be temperature controlled. This cost-effective actuator can output power that can be over 100 times that of human

muscles. Various robotic fingers based on fishing line actuators have, therefore, been developed [16]–[18]. Since these non-conductive fishing line actuators can only be controlled by temperatures, they can only be driven by hot air or water, which may limit their wider applications. Also, the mechanical strength of fishing line actuators is low, so they can be easily damaged when in use.

The SMA-fishing-line actuator, the combination of SMA wires and fishing lines, was firstly designed and implemented by Xiang *et al.* [19]. Several distinctive advantages have been identified by using SMA-fishing-line actuators, including 1) displacements of both fishing line actuators and SMA wires can be controlled by electric signals alone, leading to easier control systems; 2) the mechanical strength of fishing line actuators can be enhanced by coupling SMA wires; 3) the contraction of the SMA-fishing-line actuator can be higher (7.3 % [19]) than SMA wires alone; and 4) the hysteresis characteristic of the SMA-fishing-line actuator can be less severe than SMA wires. However, the disadvantages of the SMA-fishing-line actuator are obvious, including that 1) it cannot realize bending motions using only one SMA-fishing-line actuator; and 2) its response time is still relatively slow.

McKibben muscle actuators have larger output displacements and greater output forces. McKibben muscle actuators are linear actuators, comprising both expansive and contractive motions. When the wind angle, θ, of a McKibben muscle braided shell is larger than $54° \ 44'$, the McKibben muscle actuator belongs to an expansive actuator. When θ is smaller than $54° \ 44$, the McKibben muscle actuator is a contractive actuator [20], [21]. Extensor actuators allow robotic arms to reach higher curvatures while contractile actuators grant higher force. Expansive McKibben muscle actuators have been used in this work. Similar to the SMA-fishing-line actuator, two or more actuators should be applied to realize bending motions. In addition, they are not good at accurate movements. In practical application the muscles are either used in an antagonistic mode through two McKibben muscles, as a parallel robot or as a combination of many McKibben muscles. Kang *et al.* [22], designed an antagonistic arm driven by two McKibben muscles, I.D.Walker *et al.*, designed one kind of continuum arm driven by seven McKibben muscles [22] and Zhu Xiaocong *et al.*, designed a parallel robot driven by three Festo Muscles [23]. In some references, McKibben muscles are driven by hydraulic instead of pneumatic pressure to increase the stiffness and accuracy, such as [24] and [25]. However, this method can increase the weight of McKibben muscle, add to the complexity of the system, which is too bulky.

Controllability is vital for any robot system. Various control algorithms such as neural networks controllers [26]–[29], fuzzy PID controllers [30], sliding mode force control strategies [31], and boundary control methods [32], have been used. In this paper, a PID control method was used to control the SFLM.

In this paper we report the development of a novel and cost-effective actuator, SMA-fishing-line-McKibben

muscle (SFLM) actuator, by a simple integration of a SMA-fishing-line actuator and a McKibben muscle actuator. This novel actuator can produce bending motions which are not possible to be realized by SMA-fishing-line actuators or a McKibben muscle. The results presented in this paper show that the controllability of the new actuator is better than that of a McKibben muscle alone. The proposed actuator was able to produce the maximum output force of 3.0 N and a maximum bending angle of 61°. This may significantly promote the application of McKibben muscle and fishing line actuator technologies.

In section II of the paper, the structural design and working principle of the SFLM actuator is introduced. The SFLM was evaluated in terms of maximum bending angle and output force. After this, a three-fingered SFLM gripper is demonstrated in section III, where its maximum carrying capacity was investigated. Conclusion and future work are presented in section IV.

II. DESIGN AND PERFORMANCE EVALUATION OF THE SMA-FISHING-LINE-MCKIBBEN BENDING ACTUATOR
The proposed SFLM actuator was fabricated by a simple integration of a SMA-fishing-line actuator and a McKibben actuator. The SFLM actuator was able to realize bending motions with improved control precision. In this section, the design and performance evaluation of the SFLM actuator are demonstrated in detail.

A. DESIGN OF THE SFLM ACTUATOR
The cross-sectional structure of the SFLM actuator is demonstrated in Figure 1 (a), where a retracting spring was employed to restore elastic energy to reset the position of the SFLM actuator after bending. When inflated with high pressure gas into the McKibben muscle alone, bending movements can be achieved. This was because the stiffness of SMA-fishing-line was larger than the restoring spring. As shown in Figure 1 (b), F_m is the output force of the McKibben muscle; F_s is the output force of the restoring spring; F_f is the force caused by the SMA-fishing-line. When inflated the McKibben muscle, bending motions can be generated due to the fact that F_f is always larger than F_s. If the SMA-fishing-line is then actuated, the output force of the
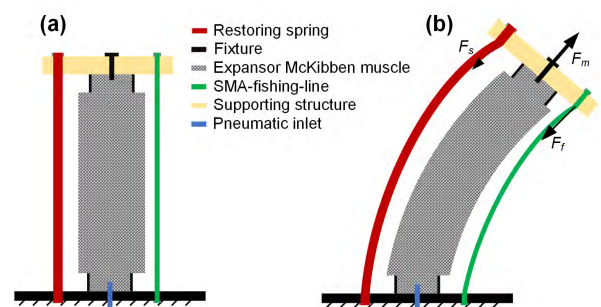

FIGURE 1. Working principle of the SFLM when it is (a) no inflated and (b) inflated.

SFLM actuator can be even larger and more accurate bending motions can be achieved.

The 3D model of the proposed SFLM is shown in Figure 2(a), which consists of one supporting structure, one expansive McKibben muscle, one restoring spring, one SMA-fishing-line, one hinge, and one guide frame. The function of the guide frame was to guide the motion direction of the SMA-fishing-line, and prevent heating from the SMA-fishing-line. The physical prototype of the SFLM actuator is presented in Figure 2 (b). The diameter of McKibben muscle and SMA-fishing-line is 20mm and 2.5 mm, respectively, and the length of both McKibben muscle and SMA-fishing-line both is 130 mm. The total weight of SFLM is 65.6 g.
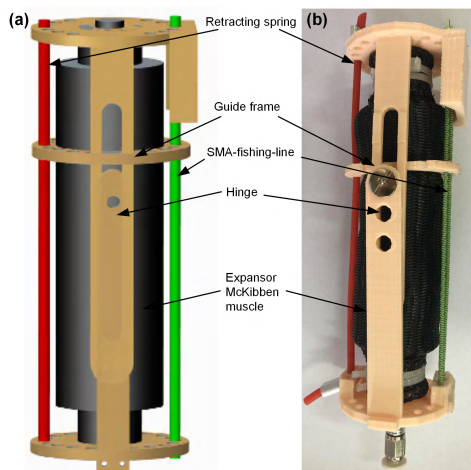

FIGURE 2. The SFLM: (a) 3D CAD model and (b) prototype.

B. OTHER RECOMMENDATIONS

A customized bending performance test rig was established and can be seen in Figure 3, where a coordinate paper was used to measure the bending angles. The McKibben muscle of the SFLM actuator was pressurized by a pump through a pneumatic triplex (to filter the air) and a solenoid valve (to regulate the air pressure). A pressure sensor (Honeywell 40PC150G2A) was used to measure the internal pressure of the SFLM actuator and then recorded by an Arduino MEGA 2560 connected to a PC. The bending testing of the SFLM actuator was conducted when the internal pressure of the McKibben muscle increased from 0 to 1 bar, with an increment of 0.2 bar. The result can be seen in Figure 4, where the maximum bending angle (the rotation of the end face) of the SFLM actuator was 61° when the internal pressure was 1 bar.

C. OUTPUT FORCE MEASUREMENT (THE SIDE FORCE CAUSED BY BENDING) OF THE SFLM ACTUATOR

The output force (the side force caused by bending) measurement setup can be seen in Figure 5, where a force sensor (Interlink Electronics, FSR402) was employed to measure the output force of the SFLM actuator. The sensitivity of the force sensor was 0.2 N and measurement range was
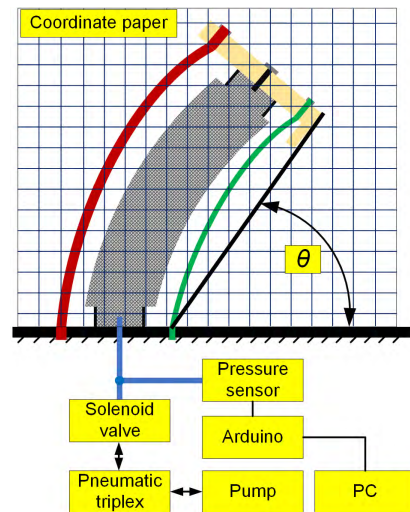

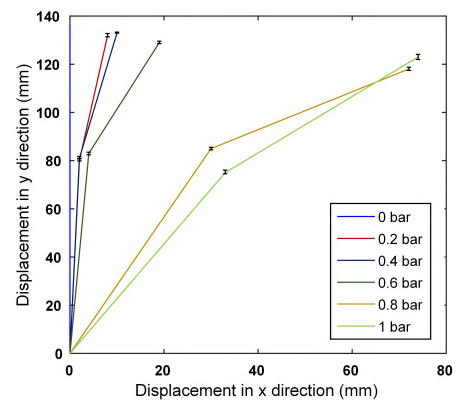**FIGURE 3. Schematic diagram of the SFLM bending testing platform.**

FIGURE 4. The bending performance of the SLFM actuator.
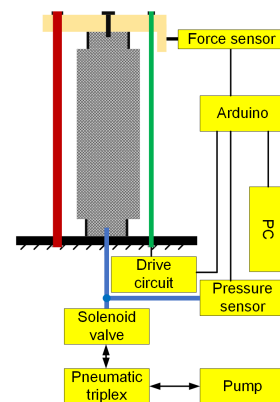

FIGURE 5. Schematic diagram of the SFLM output force testing platform.

from 0.2 to 20 N, with an accuracy of ±2 %. The SMA-fishing-line was controlled by the Arduino through a drive circuit to increase the output force of the SFLM actuator. When the SMA-fishing-line was not actuated, the output force testing of the SFLM actuator was conducted when the internal pressure of the McKibben muscle increased from 0 to 1 bar, with an increment of 0.2 bar. The results can be seen in Figure 6, where the maximum output force of

the SFLM actuator was 2.9 N when the internal pressure was 1 bar. When the SMA-fishing-line was actuated at 5 V and the McKibben muscle was pressurized from 0 to 1 bar, with an increment of 0.2 bar, as can be seen in Figure 6, the maximum output force of the SFLM actuator was 3.0 N when the internal pressure was 1 bar. For different pressures, 5 tests were conducted. It is obvious from Figure 6 that: 1) the output force of SFLM increases as the pressure increases; and 2) the actuation of the SMA-fishing-line can slightly increase the output force of the SFLM actuator.

D. FORCE CONTROL OF THE SFLM ACTUATOR

As mentioned previously, the SMA-fishing-line can slightly increase the overall output force of the SFLM. For the SMA-fishing-line, the response time of the SMA-fishing-line is much longer than McKibben muscles [19]. McKibben muscles are usually controlled by solenoid valves. It is often hard to control them precisely due to the nonlinearity of the air. In this paper, the McKibben muscle and SMA-fishing-line were controlled individually to supplement their disadvantages.

The control system of the SFLM can be seen in Figure 6. There are two PID controllers to control the McKibben Muscle and SMA-fishing-line individually. The PID controller of the McKibben muscle will work first, and the output force of SFLM will be near the target quickly. A threshold was arranged in front of the PID controller of the SMA-fishing-line, which was set as 0.2N. When the error was less than 0.2 N, the PID controller of the SMA-fishing-line will be operated. The controller of the SMA-fishing-line can compensate the output accuracy of the SFLM. In order to verify the control effects of the SFLM, the SFLM output force testing platform of Figure 5 was used again.

During experiments, the control system was setup in real time windows target of MATLAB, and the output forces of the SFLM were recorded and sent to the PC through Arduino, then the McKibben muscle and SMA-fishing-line were controlled. Based on the theory of Ziegler-Nichols, the PID parameters of the McKibben muscle controller were
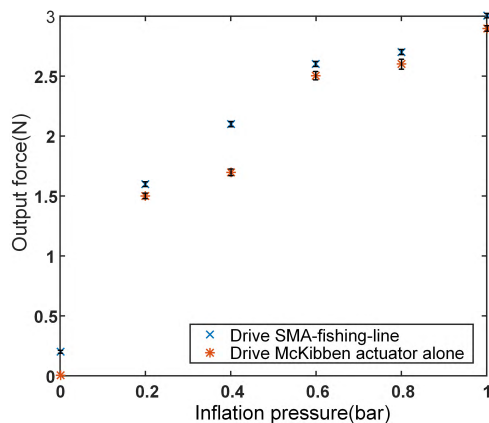
$P = 2.1$, $I = 0.4$, and $D = 0$; the PID parameters of SMA-fishing-line were $P = 55$, $I = 30$, and $D = 0$. In order to verify the control effect of the SFLM control system depicted in Figure 7, experiments were conducted. Two control modes were explored. The first control mode was used to control the McKibben muscle alone and the second approach was used to control both the McKibben muscle and SMA-fishing-line simultaneously. The two control modes were used to track 0.5 N and 1 N step signals respectively. The control results are shown in Figure 8 and Figure 9.
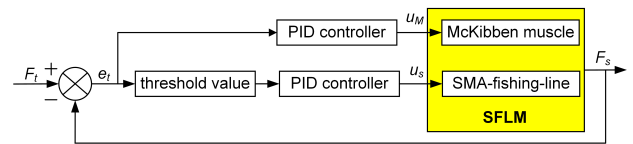

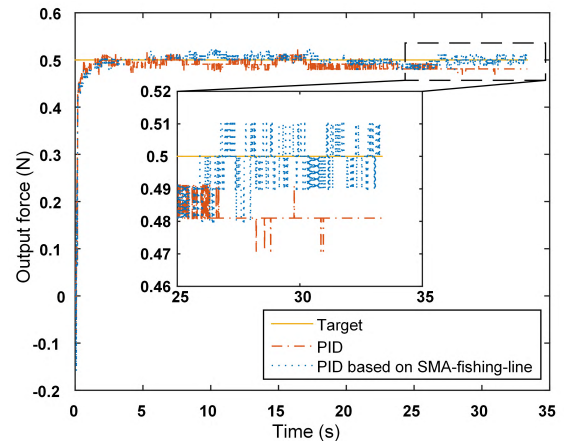**FIGURE 7. Control system diagram of SFLM.**

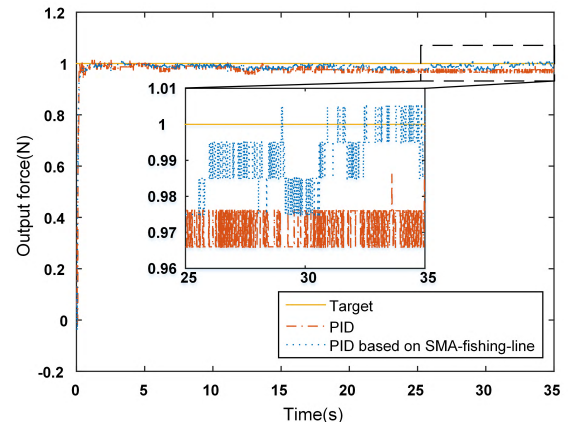**FIGURE 8. Control effects of tracking 0.5 N for SFLM.**

FIGURE 9. Control effects of tracking 1 N for SFLM.

Figure 8 and 9 show the control effects of these two control modes respectively, which implies that the PID controller

FIGURE 6. The output force of the SLFM actuator.

based on the SMA-fishing-line and McKibben muscle was better than the PID controller for controlling the McKibben muscle alone. Because of the McKibben muscle effects, the settling time of the SFLM is less than 1 s, and the response time of SFLM is much quicker than SMA-fishing-line muscles. In order to compare these two controllers, a criterion was used to evaluate the overall control accuracy, it was shown in the following function:

$$e_{mean} = \frac{\sum\limits_{k=1}^{N} |y_d(k) - y(k)|}{N} \times 100\%$$

where e_{mean} is the steady-state mean error ratio; $y_{d(k)}$ and $y_{(k)}$ are the desired displacement and actual output displacements at the time instant k, respectively and N is the total sample time number. For the PID controller of Figure 7, tracking the 0.5N step signal and 1N step signal were 0.56% and 1.15% respectively. However, for the PID controller controlling the McKibben muscle independently the values were 1.55% and 2.78%, respectively. This proved that the PID controller for controlling the McKibben muscle and SMA-fishing-line possessed a better control precision than PID controller for controlling McKibben muscle independently.

III. CASE STUDY: A THREE-FINGERED SFLM GRIPPER

A three-fingered SFLM gripper driven by three SFLMs was designed for a case study, and the three SFLMs were evenly fixed on a round plate. The total weight of the SFLM gripper was 297.2 g. Grasp experiments were performed, one of which is shown in Figure 10. Then the loading experiment was carried out in order to test the carrying capacity of the three-fingered SFLM gripper. The carrying capacity measurement setup for the three-fingered SFLM gripper can be seen in Figure 11, it includes a three-fingered SFLM gripper, a syringe and a beaker. During experiments the drive voltages for all SMA-fishing-lines were maintained at 5 V, and the pressure for all three McKibben muscles were maintained at 1 bar. The water in the beaker was gradually increased through the syringe until the beaker was dropped from the SFLM gripper. Through experiments, the carrying capacity of the three-fingered gripper was found to be 650.4 ± 0.2 g.

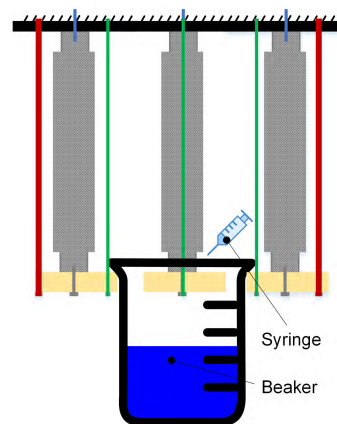**FIGURE 10. Grasping of a bottle of water using the SFLM gripper.**

FIGURE 11. Schematic experimental setup for maximum carrying capacity measurement.

IV. CONCLUSION AND FUTURE WORK

SMA-fishing-line and McKibben muscle actuators possess many advantages, such as lightweight and cost-effectiveness. However, they also possess several disadvantages. For instance, they cannot realize bending motions using only one SMA-fishing-line actuator or one McKibben muscle. Furthermore, for SMA-fishing-line actuators, their cooling times are relatively long. For McKibben muscles, it is hard to realize accurate movements.

In this research, a novel actuator, lightweight, SFLM actuator, made of SMA-fishing-line and McKibben muscle has been presented. It possesses several advantages, including 1) SFLM can realize bending motions; 2) the settling time for the SFLM (less than 1 s) was improved significantly in contrast with the SMA-fishing-line; and 3) the proposed control method, based on a SMA-fishing-line and McKibben muscle possessed higher motion accuracy (the steady-state mean error ratio is 0.56%) than the motion accuracy of McKibben muscle(the steady-state mean error ratio is 1.55%). Comparative experiments based on traditional PID motion control of the SFLM were designed, which proves that the accuracy of SFLM is indeed enhanced. A case study has been carried out on a three-fingered SFLM gripper driven by three SFLMs, through the experiments of carrying capacity it is shown that the maximum carrying capacity is 650.4 ± 0.2 g.

REFERENCES

[1] D. Caldwell, N. Tsagarakis, and G. Medrano-Cerda, "Bio-mimetic actuators: Polymeric pseudo muscular actuators and pneumatic muscle actuators for biological emulation," *Mechatronics*, vol. 10, no. 4, pp. 499–530, Jun. 2000.

[2] H. Wang, C. Wang, W. Chen, X. Liang, and Y. Liu, "Three-dimensional dynamics for cable-driven soft manipulator," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 1, pp. 18–28, Sep. 2017.

[3] H. Wang, R. Zhang, W. Chen, X. Liang, and R. Pfeifer, "Shape detection algorithm for soft manipulator based on fiber Bragg gratings," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 6, pp. 2977–2982, Sep. 2016.

[4] S. Haddadin, A. Albu-Schäffer, and G. Hirzinger, "Requirements for safe robots: Measurements, analysis and new insights," *Int. J. Robot. Res.*, vol. 28, nos. 11–12, pp. 1507–1527, Aug. 2009.

[5] Z. Chen, Y. Shen, N. Xi, and X. Tan, "Integrated sensing for ionic polymer–metal composite actuators using PVDF thin films," *Smart Mater. Struct.*, vol. 16, no. 2, pp. s262–s271, Mar. 2007.

[6] R. K. Jain, S. Majumder, and A. Dutta, "SCARA based peg-in-hole assembly using compliant IPMC micro gripper," *Robot. Auton. Syst.*, vol. 61, no. 3, pp. 297–311, Mar. 2013.

[7] U. Deole, R. Lumia, M. Shahinpoor, and M. Bermudez, "Design and test of IPMC artificial muscle microgripper," *J. Micro-Nano Mechatron.*, vol. 4, no. 3, pp. 95–102, Dec. 2008.

[8] S. Shu, D. Lagoudas, D. Hughes, and J. T. Wen, "Modeling of a flexible beam actuated by shape memory alloy wires," *Smart Mater. Struct.*, vol. 6, no. 3, pp. 264–275, Feb. 1997.

[9] C. Haines *et al.*, "Artificial muscles from fishing line and sewing thread," *Science*, vol. 343, no. 6173, pp. 868–872, Feb. 2014.

[10] J. Guo, K. Elgeneidy, C. Xiang, N. Lohse, L. Justham, and J. Rossiter, "Soft pneumatic grippers embedded with stretchable electroadhesion," *Smart Mater. Struct.*, vol. 27, no. 5, pp. 1–10, Mar. 2018.

[11] C. Chou and B. Hannaford, "Measurement and modeling of McKibben pneumatic artificial muscles," *IEEE Trans. Robot. Autom.*, vol. 12, no. 1, pp. 90–103, Feb. 1996.

[12] V. Farias, L. Solis, L. Melendez, C. Garcia, and R. Velazquez, "A four-fingered robot hand with shape memory alloys," in *Proc. AFRICON*, Sep. 2009, pp. 1–6.

[13] S. Jung, J. Bae, and I. Moon, "Lightweight prosthetic hand with five fingers using SMA actuator," in *Proc. Control, Autom. Syst. (ICCAS)*, Oct. 2011, pp. 1797–1800.

[14] N. F. Rad *et al.*, "Design and fabrication of a gripper actuated by shape memory alloy spring," in *Proc. 4th Int. Conf. Robot. Mechatronics (ICROM)*, Oct. 2016, pp. 455–458.

[15] K. J. De Laurentis, A. Fisch, J. Nikitczuk, and C. Mavroidis, "Optimal design of shape memory alloy wire bundle actuators," in *Proc. Robot. Autom. (ICRA)*, May 2002, pp. 2363–2369.

[16] J. Madden and S. Kianzad, "Twisted lines: Artificial muscle and advanced instruments can be formed from nylon threads and fabric," *IEEE Pulse*, vol. 6, no. 1, pp. 32–36, Jan./Feb. 2015.

[17] L. Wu *et al.*, "Nylon-muscle-actuated robotic finger," *Active Passive Smart Struct. Integr. Syst.*, vol. 9431, p. 94310I, Apr. 2015.

[18] K. Cho *et al.*, "A robotic finger driven by twisted and coiled polymer actuator," *Electroactive Polymer Actuat. Devices*, vol. 9798, p. 97981J, Apr. 2016.

[19] C. Xiang *et al.*, "The design, hysteresis modeling and control of a novel SMA-fishing-line actuator," *Smart Mater. Struct.*, vol. 26, no. 3, pp. 1–11, Feb. 2017.

[20] W. McMahan, V. Chitrakaran, and M. Csencsits, "Field trials and testing of the OctArm continuum manipulator," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, Jun. 2006, pp. 2336–2341.

[21] F. Connolly, P. Polygerinos, C. J. Walsh, and K. Bertoldi, "Mechanical programming of soft actuators by varying fiber angle," *Soft Robot.*, vol. 2, no. 1, pp. 26–33, Mar. 2015.

[22] B. Kang, C. S. Kothera, B. K. S. Woods, and N. M. Wereley, "Dynamic modeling of Mckibben pneumatic artificial muscles for antagonistic actuation," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2009, pp. 182–187.

[23] X. Zhu, G. Tao, B. Yao, and J. Cao, "Integrated direct/indirect adaptive robust posture trajectory tracking control of a parallel manipulator driven by pneumatic muscles," *IEEE Trans. Control Syst. Technol.*, vol. 17, no. 3, pp. 576–588, May 2009.

[24] C. Xiang, M. E. Giannaccini, T. Theodoridis, L. Hao, S. Nefti-Meziani, and S. Davis, "Variable stiffness McKibben muscles with hydraulic and pneumatic operating modes," *Adv. Robot.*, vol. 30, no. 13, pp. 889–899, Apr. 2016.

[25] R. Tiwari, M. Meller, and K. Wajcs, "Hydraulic artificial muscles," *J. Intell. Mater. Syst. Struct.*, vol. 23, no. 3, pp. 301–313, Mar. 2012.

[26] W. He, Y. Dong, and C. Sun, "Adaptive neural impedance control of a robotic manipulator with input saturation," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 46, no. 3, pp. 334–344, Mar. 2015.

[27] W. He, Z. Yan, C. Sun, and Y. Chen, "Adaptive neural network control of a flapping wing micro aerial vehicle with disturbance observer," *IEEE Trans. Cybern.*, vol. 47, no. 10, pp. 3452–3465, Oct. 2017.

[28] C. Sun, W. He, and J. Hong, "Neural network control of a flexible robotic manipulator using the lumped spring-mass model," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 47, no. 8, pp. 1863–1874, Aug. 2017.

[29] H. Gao, W. He, C. Zhou, and C. Sun, "Neural network control of a two-link flexible robotic manipulator using assumed mode method," *IEEE Trans. Ind. Informat.*, pp. 1–10, Mar. 2018.

[30] X. Chang and J. H. Lilly, "Fuzzy control for pneumatic muscle tracking via evolutionary tuning," *Intell. Autom. Soft Comput.*, vol. 9, no. 4, pp. 227–244, Mar. 2003.

[31] B. Kang, "Compliance characteristic and force control of antagonistic actuation by pneumatic artificial muscles," *Meccanica*, vol. 49, no. 3, pp. 565–574, Mar. 2014.

[32] W. He and S. Zhang, "Control design for nonlinear flexible wings of a robotic aircraft," *IEEE Trans. Control Syst. Technol.*, vol. 25, no. 1, pp. 351–357, Jan. 2017.

CHAOQUN XIANG received the B.Eng. and M.Sc. degrees in mechanical design and theory from the Liaoning University of Technology, China, in 2009 and 2012, respectively, and the Ph.D. degree in mechatronic engineering from Northeastern University, China, in 2017. He was a Visiting Researcher with the Centre for Robotics and Autonomous System Robotics, Salford University, U.K. He is currently with the Bristol Robotics Laboratory, University of Bristol, U.K., as a Research Associate in soft robotics. His main research interests include bionic drivers of artificial muscles and intelligent control methods for soft robots.
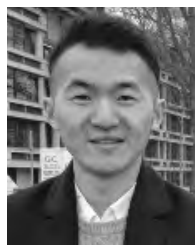
JIANGLONG GUO received the B.Eng. degree in mechanical engineering and automation from Northeastern University, China, in 2012, and the Ph.D. degree from Loughborough University in 2016. From 2016 to 2017, he was a Research Associate with the EPSRC Centre for Innovative Manufacturing in Intelligent Automation, Loughborough University. He is currently with the Bristol Robotics Laboratory, University of Bristol, U.K., as Research Associate in soft robotics. His research interests are multidisciplinary in nature, including employing electroadhesion in both rigid and soft robotic grasping applications, bio-inspired robotics (such as FMAV, hopping robots, and crawling/climbing robots), surface texture measurement and characterization, and smart sensors and actuators.

YANG CHEN received the B.Eng. degree in mechanical engineering and automation from the China University of Mining and Technology, China, in 2012, and the M.S. degree in mechatronic engineering from Northeastern University, China, in 2014. He is currently pursuing the Ph.D. degree with Northeastern University, China. His research interests include driving, modeling and control of artificial muscles especially for IPMCs, SMAs, and soft robotic systems.

LINA HAO received the Ph.D. degree in control theory and control engineering from Northeastern University, China, in 2001. She was a Visiting Researcher with Michigan State University, USA, from 2005 to 2006. She is currently a Professor with the School of Mechanical Engineering and Automation, Northeastern University, China. She is a fellow of the IEEE Robotics and Automation Society and the International Society of Bionic Engineering. Her main research interests include design and control of micro–nano robotic systems, bionic drivers of artificial muscles, and smart sensors and actuators.

STEVE DAVIS received the degree in robotic and electronic engineering from the University of Salford in 1998, the M.Sc. degree in advanced robotics in 2000, and the Ph.D. degree in 2005. He then became a Research Fellow before moving to the Italian Institute of Technology in 2008 as a Team Leader. He returned to Salford in 2012 as a Lecturer in manufacturing automation and robotics. He has published extensively and has also co-authored chapters in two books on automation. His research interests include actuators, biologically inspired systems, biomimetics, soft robotics, humanoid robots, end-effectors, and dexterous hands and industrial automation, particularly in the food industry. He has been an associate editor of several IEEE conferences and is a Guest Editor of a special edition of the journal, Actuators. He has experience of attracting research funding, most notably the €3,948,470 Marie Curie Initial Training Networks Sustainable Manufacturing through Advanced Robotics Training in Europe.

● ● ●