2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
October 25-29, 2020, Las Vegas, NV, USA (Virtual)

Novel Design of a Soft Pump Driven by Super-Coiled Polymer Artificial Muscles

Yu Alexander Tse, Ki Wan Wong, Yang Yang*, *Member, IEEE*, and Michael Yu Wang, *Fellow, IEEE*

***Abstract*— The widespread use of fluidic actuation for soft robots creates a high demand for soft pumps and compressors. However, current off-the-shelf pumps are usually rigid, noisy, and cumbersome. As a result, it is hard to integrate most commercial pumps into soft robotic systems, which restricts the autonomy and portability of soft robots. This paper presents the novel design of a soft pump based on bellow structure and super-coiled polymer (SCP) artificial muscles. The pump is flexible, lightweight, modular, scalable, quiet, and low cost. The pumping mechanism and fabrication process of the proposed soft pump is demonstrated. A pump prototype is fabricated to verify the proposed design and characterize its performance. From the characterization results, the pump can reach an output flow rate of up to 54 ml/min and delivers pressure up to 2.63 kPa. The pump has potential applications in untethered soft robots and wearable devices.**

I. Introduction

The past decades have witnessed massive progress in the research of soft robots and their applications, such as rehabilitation [1], medical devices [2], human-centered grasping and manipulation [3, 4], field exploration [5, 6], etc. The advantages of soft robots over traditional rigid bodied robots come from the elasticity and compliance of deformable materials that they are made of [7]. With the growth of soft robots, the investigation of soft actuators has also attracted a lot of research interests. Conventional soft actuation technologies include soft fluidic actuators [8, 9], shape memory alloy (SMA) actuators [10], shape memory polymer (SMP) actuators [11] and electro-active polymer (EAP) actuators [12, 13]. Among them, soft fluidic actuators, especially soft pneumatic actuators, are the most popular for soft robots' actuation due to their simple controllability, high power density, and fast response [14]. Soft fluidic actuators can achieve different motions: expanding [15], contracting [16], twisting [17], and bending [18], making them suitable for a variety of soft robotic applications.

Research is supported by the Startup Foundation for Introducing Talent of NUIST under Project 1441092001001, and the Hong Kong Innovation and Technology Fund (ITF) ITS-018-17FP.

Y. Tse, and K. Wong are with the Department of Mechanical and Aerospace Engineering, Hong Kong University of Science and Technology, Hong Kong, China.

*Y. Yang (corresponding author) is with School of Automation, Nanjing University of Information Science and Technology, Nanjing, China and also with the Department of Mechanical and Aerospace Engineering, Hong Kong University of Science and Technology, Hong Kong, China (e-mail: meyang@nuist.edu.cn).

M. Y. Wang is with the Department of Mechanical and Aerospace Engineering, and Department of Electronic and Computer Engineering, Hong Kong University of Science and Technology, Hong Kong, China.

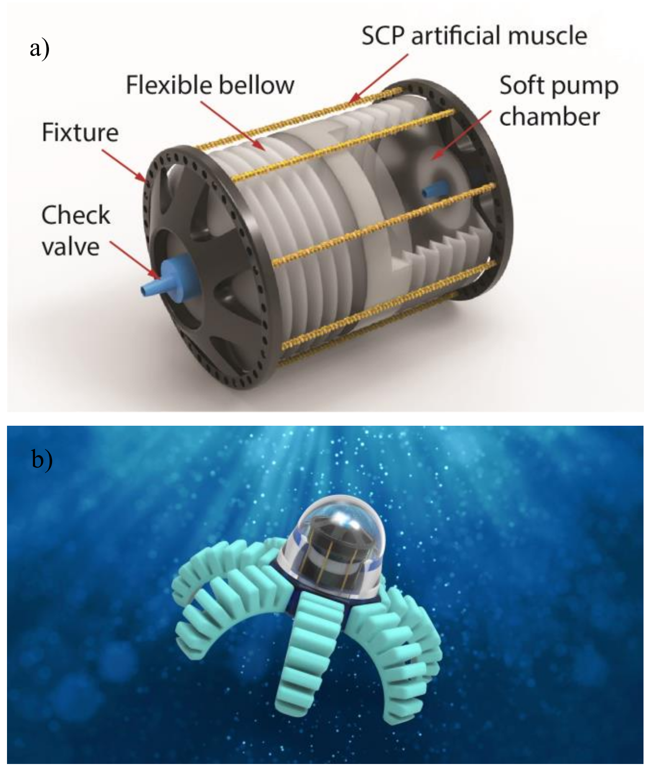

Fig. 1. Proposed novel soft pump and its possible applications. (a) The pump model. (b) Application of the pump in powering untethered soft robot.

Pressure generation of soft fluidic actuators mostly relies on mechanical pumps or compressors, which are usually rigid, bulky, and noisy. The introduction of rigid pumps makes the whole soft robotic system less compact and impede the compliance of soft robots. The lack of soft pumps has restricted the portability and autonomy of soft robots [9]. Therefore, there is a high demand for the study of soft and flexible pumps, which attracts many researchers to make tentative exploration in this area. Most existing soft pumps are in microscale and aimed for micro-electromechanical systems (MEMS) applications with limited flow rate and pressure [19]. Stergiopulos et al. investigated a soft pump driven by Methane (CH4) combustion and could achieve high pressure (above 50 kPa) [20]. However, controllability is a challenge for pumps using combustion as an actuation source, and the device development needs considerable effort to tolerate the high combustion pressure and temperature [21]. Recently, Cacucciolo et al. proposed a soft stretchable pump based on charge-injection electro-hydrodynamics [22]. The pump exhibited a maximal pressure of 14 kPa and a maximal flow rate of 6 ml/min. In their study, applications in wearable devices for on-body thermal regulation and autonomous soft

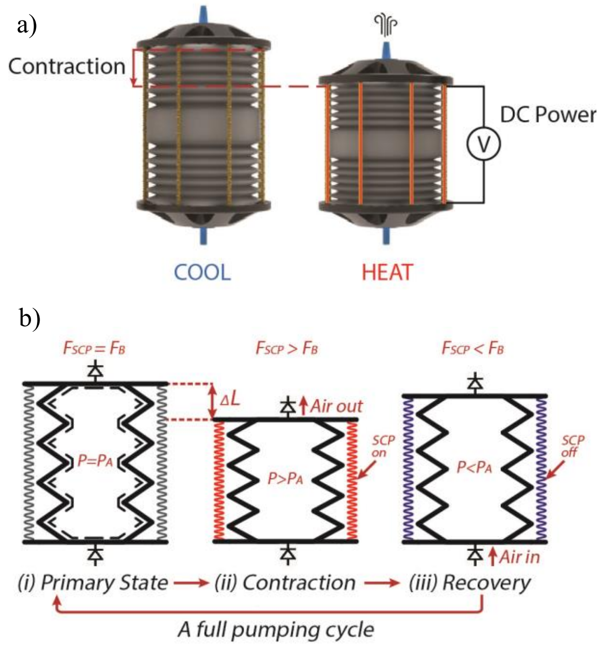

Fig. 2. Working principle of the proposed soft pump. (a) Prototype demonstration. (b) Diagram showing a full pumping cycle.

robots were also presented. However, the driving voltage needs at least 2.5 kV, and the micro-fabrication techniques required for such designs are intricate and costly.

In this research, we present the novel design of a soft pump, which is low-cost and can be easily fabricated. The pump consists of soft bellow membranes, two check valves, and a set of SCP artificial muscles as shown in Fig. 1(a). SCP artificial muscles are novel and recently discovered soft actuators that possess several unique properties such as high power density, excellent customizability, silent actuation, and low cost [23, 24]. So far, SCP artificial muscles have been adopted into many robotic applications, including humanoid robotic hand [25], inchworm-like crawling robot [26], variable stiffness actuator [27], controllable shape morphing structure [28], and soft manipulator [29], etc.

In this study, we use these SCP artificial muscles to actuate a soft pump, which to the best of our knowledge, is the first to report such kind of applications. With the proposed soft pump, autonomous and untethered soft robotic applications such as a underwater jellyfish inspired robot with its legs realized by soft fluidic actuators presented in Fig. 1(b) would be possible. Benefited from the superiorities of the proposed soft pump, the jellyfish robot would be silent, lightweight, more squeezable and without the trouble of tethering, making it more autonomous and competent in performing underwater exploration tasks.

Contributions of this work are listed as follows:

1) The novel design of a soft and flexible pump enabled by bellow structure and SCP artificial muscles;

2) Low-cost and straightforward fabrication of the soft pump is realized;

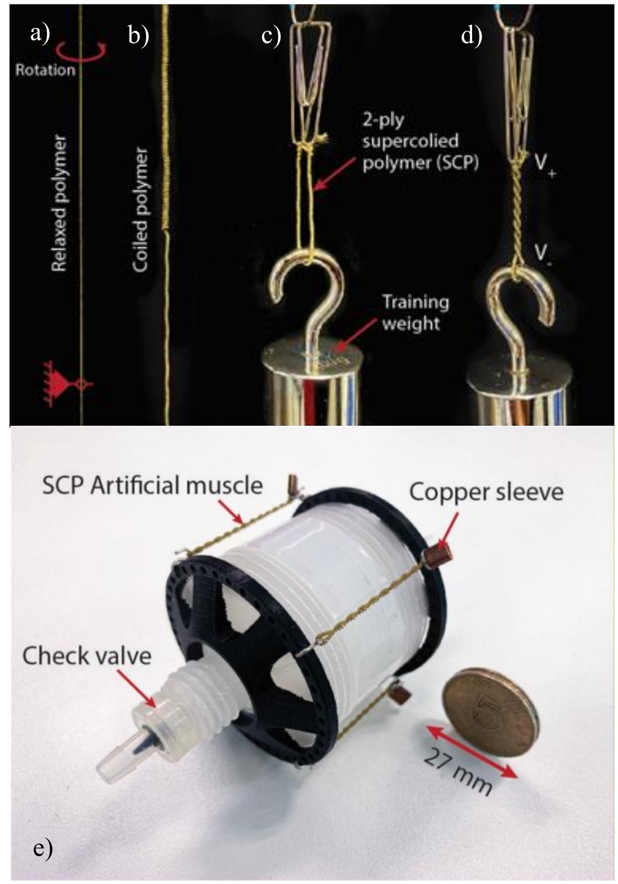

Fig. 3. Fabrication process of a soft pump. (a) – (d) Fabrication and training of the SCP artificial muscles. (e) Real prototype of the fabricated pump (a five- Hong Kong dollar coin is put beside the pump for reference).

3) The proposed pump is compact, silent, customizable, and promising for applications in artificial organs, untethered soft robots, and wearable devices.

The rest of this paper is organized in the following manner. Section II presents the design and working principle of the soft pump. Section III illustrates the fabrication and characterization of pump performance in detail. Finally, Section IV summarizes the paper and discusses future work.

II. Design and Working Principle

The pumping mechanism can be explained as follows (shown in Fig. 2(a)). Soft bellow membrane is contracted when SCP actuators are powered on and is deformed from its primary shape, contributed by the flexibility of its material nature. When SCP actuators are powered off. The contraction stops and the bellow starts to recover. The volume change of the bellow's inner chamber leads to a pressure difference between the inner chamber and the ambient environment. As a result, gas or liquid would flow in and out. The two check valves direct the flow from one side to another side of the pump, which prevents backflow and enables directional fluid circulation.

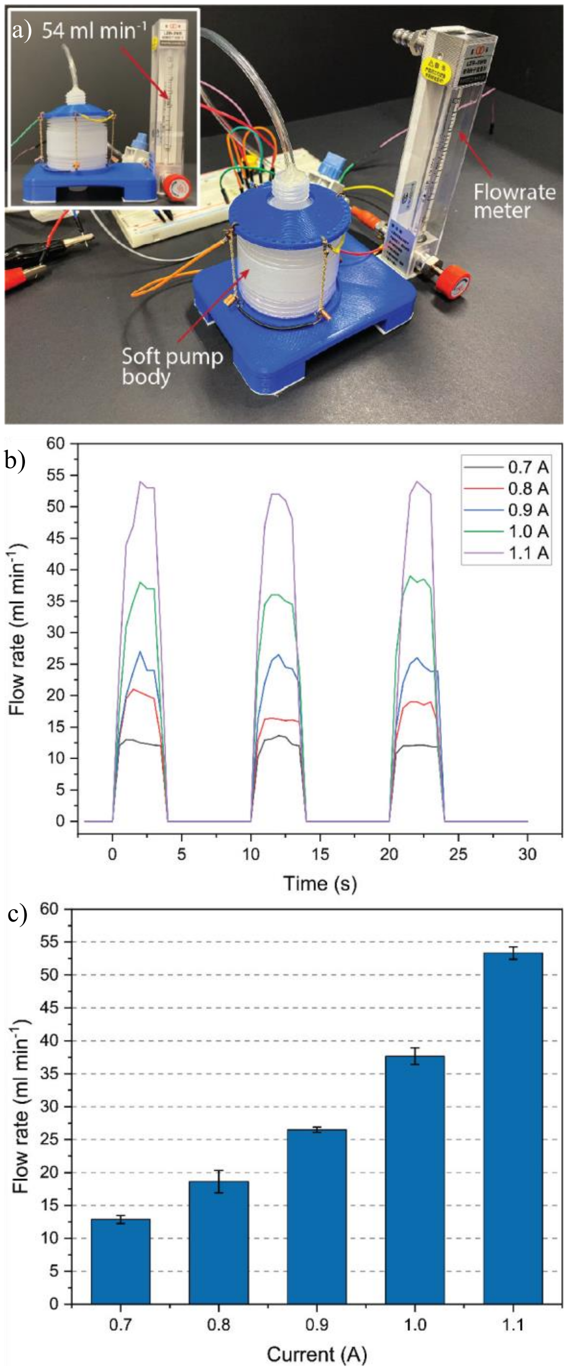

Fig. 4. Flow rate characterization experiments. (a) Custom-built experiment set-up. (b) Relationship between flow rate and time under five different currents, each repeated three times. (c) Relationship between average maximal flow rate and current with standard deviation depicted.

Fig. 2(b) explains the detailed working principle in a full pumping cycle. At the primary state, the SCP artificial muscles are at rest. To guarantee contraction upon heating, the SCP artificial muscles are assembled to the soft bellow with a pretension. The elastic force of the bellow F_B and the contraction force of SCP artificial muscles FSCP (produced by the pre-stress during assembly) achieve a balance at this state (shown in Fig. 2(b)(i)). When SCP artificial muscles are powered on and thus heated, thermal expansion introduced stress is generated inside the artificial muscles. As a result, the contraction force of SCP artificial muscles F_{SCP} exceeds the elastic force of the bellow F_B and the bellow would contract with a distance ΔL. With the volume of the bellow reduced, the air pressure inside the pump P becomes larger than the ambient pressure P_A and air would be pumped out through the check valve as presented in Fig. 2(b)(ii) until P equals to P_A. Once the SCP artificial muscles are powered off and start cooling down, FSCP becomes less than F_B and the bellow would undergo a recovery process due to its elasticity. At this stage, the volume of the bellow increases and leads to a pressure drop inside the pump ($P < P_A$). As a consequence, the ambient air flows in from the other check valve as shown in Fig. 2(b)(iii). When the bellow fully recovers to its original shape in Fig. 2(b)(i), a full pumping cycle is completed. The pump mechanism is similar for pumping liquid except that the entering check valve should be connected to a liquid supply.

III. Fabrication and Experiment

A. *Fabrication of SCP artificial muscles*

The supercoiled polymer artificial muscles were fabricated from commercially available yarns. The yarns are silver-plated，thus they can be actuated electrically to generate heat when a current pass through. In this study, we use Shieldex silver-plated cotton nylon yarns (Ne 30/1 95% Cotton + 5% Ag Nylon, PN: 700000301091) to fabricate SCP artificial muscles.

To fabricate SCP artificial muscles, one end of the yarn is fixed to a motor and the other end is attached to a weight so that the yarn is hanged vertically. A 100 g weight is used to keep the yarn straight and stretched during twisting. The motor is then turned on and spins at a constant low speed to twist the yarn (Fig. 3a). During spinning, the weight is kept from any rotation. Once coiling occurs (Fig. 3b), slow down the motor speed and keep spinning until the entire yarn is coiled. Afterward, create a 2-ply configuration by double fold the fabricated 1-ply SCP and prevent it from unwinding. A 200 g weight is then applied to the 2-ply SCP artificial muscles for annealing and training (Fig. 3c). To anneal and train, a voltage pulse (0.8V/cm, 3s on 7s off) is applied to the SCP artificial muscles constantly for 2 minutes (Fig. 3d). The annealing and training process will release the residual stress in the SCP artificial muscles and increase the actuation stroke. Detailed fabrication precautions can refer to references [23, 24].

B. *Fabrication of the Soft Pump*

The main body of the proposed soft pump (Fig. 3e) consists of two soft bellow membranes, each with a 3D printed fixture, and a check valve at each end to allow directional fluid circulation. The size of the pump body is 6 cm in height and 5 cm in diameter with an overall weight of 50 grams. The soft bellow membranes are first connected using silicone elastomer (Smooth-On Ecoflex20) to prevent fluid leakage while the bellow chambers are internally connected so fluid can travel through. These soft bellow membranes are off the shelf, low cost, and provide a wide range of stiffness and size selections. Therefore, the soft pump can be easily scaled up or down. Afterward, a fixture is glued to each end of the soft pump body to mount the SCP artificial muscles and to apply pressure evenly to the soft bellow membranes. The fixtures

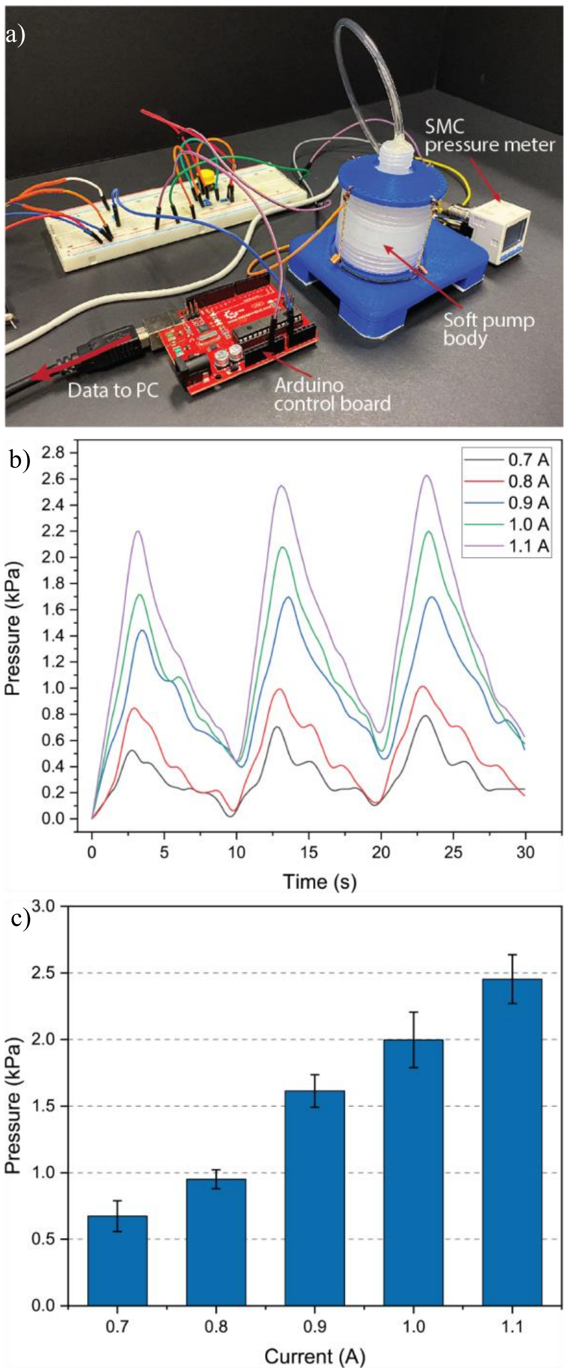

Fig. 5. Output pressure characterization experiments. (a) Custom-built experiment set-up (b) Relationship between output pressure and time under five different current, each repeated three times. (c) Relationship between average maximal pressure output and current with standard deviation depicted.

were 3D printed using PLA for fast prototyping and testing. However, the material can be replaced by flexible materials like thermoplastic polyurethane (TPU) or silicone elastomers to further reduce the overall stiffness of the pump. Finally, SCP artificial muscles are mounted to the fixture with conductive hooks. The SCP artificial muscles are equally spaced so that the pump contracts evenly. For the pump to work most efficiently, the pump body must have enough stiffness to keep the SCP artificial muscles prestressed. For a two-bellow pump structure, four SCP artificial muscles are used. However, the number of SCP artificial muscles can be increased by adopting a stiffer bellow membrane. Theoretically, the power of the soft pump can be increased with more SCP artificial muscles applied. To ensure each SCP artificial muscle contract evenly, they are connected in series through wires to a 12V-24V power source.

C. Characterization of Flow Rate

Flowrate measurements were performed using a custom-built experiment platform (Fig. 4(a)). The soft pump was connected to a flow rate meter (S-Huan LZB-3WB Series), which has a measuring range of 10-100 ml/min. We measured the output flowrate of the pump when applied to different currents from 0.7A to 1.1A with a 0.1A interval. For each measurement, we applied a voltage pulse (3s on 7s off) to the soft pump and repeated the cycle three times. Data was collected manually through the recorded video of the meter readings at a frequency of 6 times per second.

The flow rate and time relationships for the five applied currents flows are illustrated in Fig. 4(b). A maximum flow rate of 54 ml min^{-1} was recorded at 1.1A. From Fig. 4(c), we can see that as the current and power input for SCP artificial muscles increase, the soft pump can achieve higher max. flow rates. The fluctuation in flow rates' peak values in Fig. 4(b) may be caused by the nonuniformity of the four SCP artificial muscles being used in the pump. A video showing the flow rate test can be viewed in the Supplementary File.

D. Characterization of Output Pressure

To characterize the output pressure of the proposed soft pump, the pressure under different current flows was measured on a custom-built platform using a high precision digital pressure switch (Fig. 5(a)). The soft pump was connected to the pressure switch (SMC ZSE20CF-R-02-W Series) that has a range from -100 kPa to 100 kPa at an accuracy of 2.5% F.S. A total of five applied current flows were tested from 0.7A to 1.1A with a 0.1A interval. Same as the previous experiment, we applied a voltage pulse (3s on 7s off) to the soft pump and repeated three times. We collected the data by reading the analog voltage output of the pressure switch using a piece of Arduino board and transferred the data to a PC for analysis. The data was sampled at every 0.15 s.

The data from the pressure test was filtered with a lowpass filter to eliminate voltage spikes, which are likely caused by the unstable USB powering to the Arduino board. The plotted pressure and time relationship under different current flow is shown in Fig. 5(b). It is obvious that the soft pump can deliver higher output pressure with larger current input. In Fig. 5(b), the maximal pressure value becomes larger in each subsequent cycle. This is caused by the remnant pressurized air inside the pipe at the end of each cycle. To eliminate this effect, absolute pressure variation values are calculated for output pressure characterization presented in Fig. 5(c).

E. Comparison of Pump Performance

With the results from characterization experiments, here we summarize the Table 1 comparing our proposed soft pump performance with other pumps (from commercial companies or from research groups) based on different physical principles. Compared to commercially available pumps, soft-material

TABLE I. COMPARISON OF THE PROPOSED SOFT PUMP WITH OTHER PUMPS

Category	Pumping mechanism	Weight (g) (Power supply and controller not included)	Approximate size (cm^3)	Max. Power Consumption (W)	Max. Pressure (kPa)	Max. Flow Rate (ml/min)	Reference
Commercial minature pump (MGD 1000S)	Electro-magnetic	142	58.6	30	800	500	[30]
Current off-the-shelf compressor (McMaster STPAC)	Electro-magnetic	15422	75500	1200	1034	42500	[31]
Micro pumps	Piezoelectric	N/A	1.98	0.4	0.52	0.04	[32]
	Electroosmotic	N/A	9	0.002	33	0.02	[33]
Soft pumps	Combustion	N/A	49	N/A	60	40	[20]
	Electro-hydrodynamics	1	1.17	0.17	14	6	[22]
	Thermo-mechanical	20	80.4	19.25	2.63	54	*Current work*

pumps can hardly have comparable output pressure and flow rate. Whereas, soft pumps have light weight as well as low volume, and the flexibility resulted from use of soft materials make them more suitable to be integrated into soft robots especially for applications where external source of compressed air is impractical.

For the two representative micro pumps [32, 33], they can only generate limited flow rate and pressure, thus are typically used in lab-on-a-chip devices. From the table, we can also see that our pump surpasses previously published soft pumps in flow rates. Combustion powered pump delivers both high flow rate and pressure but usually require delicate design to bear pressure burst and is more applicable for jumping robot which require explosive motion [20]. Electrohydrodynamics based pump has the lightest weight and smallest volume [22]. The stretchable pumps have also demonstrated impressive applications in wearable device for on-body thermal regulation and in untethered actuation for soft pneumatic actuator. The limitation is flow rate is a bit low and driving voltage can be as high as several kilovolts. For our pump, the flow rate is good while pressure is limited. The output pressure can be increased by connecting several pumps in series. In future, other design parameters' (such as the number of SCP artificial muscles for each pump, dimension and elasticity of bellows) influence on the output pressure will be further investigated to improve the output pressure.

IV. CONCLUSIONS AND FUTURE WORK

In this paper, we propose a soft pump taking use of flexible bellow structure and SCP artificial muscles. Benefited from the simple design and appealing properties of the newly discovered artificial muscles, the pump is easy fabricated, low cost, quiet and most importantly flexible due to the composing soft materials. The pumping mechanism is discussed in detail. Through experimental tests, flow rate and output pressure of the pump are characterized. The proposed soft pump is promising for applications such as the integrated soft robotic system using fluidic actuators with no need for external compressors or pumps.

For future work, we will first establish the analytical model of the pump so that our design will be better guided theoretically. Especially, we hope to improve the pump performance with optimized dimension parameters and SCP artificial muscle utilization. Soft robotic applications will also be investigated such jellyfish swimming robot and soft prosthesis or wearable glove with on board pressure generation realized by this soft pump.

REFERENCES

[1] Polygerinos, P., Wang, Z., Galloway, K.C., Wood, R.J. and Walsh, C.J., 2015. Soft robotic glove for combined assistance and at-home rehabilitation. Robotics and Autonomous Systems, 73, pp.135-143.

[2] Ranzani, T., Cianchetti, M., Gerboni, G., De Falco, I. and Menciassi, A., 2016. A soft modular manipulator for minimally invasive surgery: design and characterization of a single module. IEEE Transactions on Robotics, 32(1), pp.187-200.

[3] Shintake, J., Cacucciolo, V., Floreano, D. and Shea, H., 2018. Soft robotic grippers. Advanced Materials, 30(29), p.1707035.

[4] Zhou, J., Chen, S. and Wang, Z., 2017. A soft-robotic gripper with enhanced object adaptation and grasping reliability. IEEE Robotics and automation letters, 2(4), pp.2287-2293.

[5] Tolley, M.T., Shepherd, R.F., Mosadegh, B., Galloway, K.C., Wehner, M., Karpelson, M., Wood, R.J. and Whitesides, G.M., 2014. A resilient, untethered soft robot. Soft robotics, 1(3), pp.213-223.

[6] Hawkes, E.W., Blumenschein, L.H., Greer, J.D. and Okamura, A.M., 2017. A soft robot that navigates its environment through growth. Science Robotics, 2(8), p.eaan3028.

[7] Whitesides, G.M., 2018. Soft robotics. Angewandte Chemie International Edition, 57(16), pp.4258-4273.

[8] Gorissen, B., Reynaerts, D., Konishi, S., Yoshida, K., Kim, J.W. and De Volder, M., 2017. Elastic inflatable actuators for soft robotic applications. Advanced Materials, 29(43), p.1604977.

[9] Polygerinos, P., Correll, N., Morin, S.A., Mosadegh, B., Onal, C.D., Petersen, K., Cianchetti, M., Tolley, M.T. and Shepherd, R.F., 2017. Soft robotics: Review of fluid - driven intrinsically soft devices; manufacturing, sensing, control, and applications in human - robot interaction. Advanced Engineering Materials, 19(12), p.1700016.

[10] Rodrigue, H., Wang, W., Han, M.W., Kim, T.J. and Ahn, S.H., 2017. An overview of shape memory alloy-coupled actuators and robots. Soft robotics, 4(1), pp.3-15.

[11] Liu, C., Qin, H. and Mather, P.T., 2007. Review of progress in shape-memory polymers. Journal of materials chemistry, 17(16), pp.1543-1558.

[12] Najem, J., Sarles, S.A., Akle, B. and Leo, D.J., 2012. Biomimetic jellyfish-inspired underwater vehicle actuated by ionic polymer metal composite actuators. Smart Materials and Structures, 21(9), p.094026.
[13] Chen, F., Liu, K., Wang, Y., Zou, J., Gu, G. and Zhu, X., 2019. Automatic design of soft dielectric elastomer actuators with optimal spatial electric fields. IEEE Transactions on Robotics, 35(5), pp.1150-1165.
[14] Zhang, J., Sheng, J., O'Neill, C.T., Walsh, C.J., Wood, R.J., Ryu, J.H., Desai, J.P. and Yip, M.C., 2019. Robotic Artificial Muscles: Current Progress and Future Perspectives. IEEE Transactions on Robotics, 35(3), pp.761-781.
[15] Martinez, R.V., Fish, C.R., Chen, X. and Whitesides, G.M., 2012. Elastomeric origami: programmable paper ‐ elastomer composites as pneumatic actuators. Advanced functional materials, 22(7), pp.1376-1384.
[16] Tondu, B. and Lopez, P., 2000. Modeling and control of McKibben artificial muscle robot actuators. IEEE control systems Magazine, 20(2), pp.15-38.
[17] Wang, T., Ge, L. and Gu, G., 2018. Programmable design of soft pneu-net actuators with oblique chambers can generate coupled bending and twisting motions. Sensors and Actuators A: Physical, 271, pp.131-138.
[18] Deimel, R. and Brock, O., 2016. A novel type of compliant and underactuated robotic hand for dexterous grasping. The International Journal of Robotics Research, 35(1-3), pp.161-185.
[19] Iverson, B.D. and Garimella, S.V., 2008. Recent advances in microscale pumping technologies: a review and evaluation. Microfluidics and nanofluidics, 5(2), pp.145-174.
[20] Stergiopulos, C., Vogt, D., Tolley, M.T., Wehner, M., Barber, J., Whitesides, G.M. and Wood, R.J., 2014. A soft combustion-driven pump for soft robots. In ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems. American Society of Mechanical Engineers Digital Collection.
[21] Wehner, M., Tolley, M.T., Mengüç, Y., Park, Y.L., Mozeika, A., Ding, Y., Onal, C., Shepherd, R.F., Whitesides, G.M. and Wood, R.J., 2014. Pneumatic energy sources for autonomous and wearable soft robotics. Soft robotics, 1(4), pp.263-274.
[22] Cacucciolo, V., Shintake, J., Kuwajima, Y., Maeda, S., Floreano, D. and Shea, H., 2019. Stretchable pumps for soft machines. Nature, 572(7770), pp.516-519.
[23] Haines, C.S., Lima, M.D., Li, N., Spinks, G.M., Foroughi, J., Madden, J.D., Kim, S.H., Fang, S., De Andrade, M.J., Göktepe, F. and Göktepe, Ö., 2014. Artificial muscles from fishing line and sewing thread. Science, 343(6173), pp.868-872.
[24] Yip, M.C. and Niemeyer, G., 2017. On the control and properties of supercoiled polymer artificial muscles. IEEE Transactions on Robotics, 33(3), pp.689-699.
[25] Wu, L., de Andrade, M.J., Saharan, L.K., Rome, R.S., Baughman, R.H. and Tadesse, Y., 2017. Compact and low-cost humanoid hand powered by nylon artificial muscles. Bioinspiration & biomimetics, 12(2), p.026004.
[26] Yang, Y., Tse, Y.A., Zhang, Y., Kan, Z. and Wang, M.Y., 2019, April. A Low-cost Inchworm-inspired Soft Robot Driven by Supercoiled Polymer Artificial Muscle. In 2019 2nd IEEE International Conference on Soft Robotics (RoboSoft) (pp. 161-166). IEEE.
[27] Yang, Y., Kan, Z., Zhang, Y., Tse, Y.A. and Wang, M.Y., 2019, May. A Novel Variable Stiffness Actuator Based on Pneumatic Actuation and Supercoiled Polymer Artificial Muscles. In 2019 International Conference on Robotics and Automation (ICRA) (pp. 3983-3989). IEEE.
[28] Sun, J., Pawlowski, B. and Zhao, J., 2018, October. Embedded and controllable shape morphing with twisted-and-coiled actuators. In 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) (pp. 5912-5917). IEEE.
[29] Tang, X., Li, K., Liu, Y., Zhou, D. and Zhao, J., 2019. A general soft robot module driven by twisted and coiled actuators. Smart Materials and Structures, 28(3), p.035019.
[30] MGD 1000S specification. Available at https://www.micropumps.co.uk/TCSMGD1000range.htm
[31] McMaster-Carr single tank portable air compressor specifcation. Available at: https://www.mcmaster.com/9965k62
[32] Jang, L.S., Li, Y.J., Lin, S.J., Hsu, Y.C., Yao, W.S., Tsai, M.C. and Hou, C.C., 2007. A stand-alone peristaltic micropump based on piezoelectric actuation. Biomedical microdevices, 9(2), pp.185-194.
[33] Chen, C.H. and Santiago, J.G., 2002. A planar electroosmotic micropump. Journal of Microelectromechanical Systems, 11(6), pp.672-683.