2014 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS 2014)
September 14-18, 2014, Chicago, IL, USA

Soft Pneumatic Actuator Skin with Embedded Sensors

Chansu Suh[1], Jordi Condal Margarit[2], Yun Seong Song[1] and Jamie Paik[1]

***Abstract*— Soft Pneumatic Actuator skin (SPA-skin) is a novel concept of ultra-thin (< 1 *mm*) sensor embedded actuators with distributed actuation points that could cover soft bodies. This highly customizable and flexible SPA-skin is ideal for providing proprioceptive sensing by covering pre-existing structures and robots bodies. Having few limitation of the surface quality, dynamics, or shape, these mechanical attributes allow potential applications in autonomous flexible braille, active surface pattern reconfiguration, distributed actuation and sensing for tactile interface improvements. In this paper, the authors present a proof-of-concept SPA-skin. The mechanical parameters, design criteria, sensor selection, and actuator construction process are illustrated. Two control schemes, actuation mode and force sensing mode, are also demonstrated with the latest prototype.**

I. INTRODUCTION

The Soft Pneumatic Actuators (SPA) have recently been a popular choice for many soft robotics applications due to their high customizability, light-weight. and most of all inherent safety for various human interaction applications. One of most effective ways of altering the shape and motions is to vary the design and placement of the inextensible layer [1]–[4]: this allows them to have a extensive design.

The silicone-based pneumatic actuators are widely used for the medical robots where substantial versatility and safety are required in a confined space [5], rescue robots, which operate in unstructured environment and robot hands that consist of several bendable fingers [6]. In [7], the authors developed soft robotic tentacles which have high dexterity and multiple degrees of freedom. The soft tentacle can hold, for example, a fragile flower or cup. The Flexible Micro Actuator, which is a fiberless soft actuator, was developed for medical devices [8]. It grasps a fish egg without breaking it. Furthermore, SPAs were applied to rehabilitation [9]: a rodent exoskeleton should be equipped with a compliance mechanism to protect against unexpected seizures. A SPA can be a solution to create compliance and great force. A modular soft manipulator was developed, which has a mechanism that is used to adjust the stiffness [10]. Sheperd *et al.* [11] developed a multi-gait soft robot which can crawl and overcome complicated obstacles. This robot shows the great potential of SPA by using the characteristics of its soft materials; its flexibility that helps adapt to complicate surface.

* This work is funded by the National Centre of Competence in Research (NCCR) Robotics, Switzerland

[1]Chansu Suh, Yun Seong Song and Jamie Paik are with the Reconfigurable Robotics Laboratory, Ecole Polytechnique Federale de Lausanne (EPFL), Lausanne, Switzerland jamie.paik@epfl.ch

[2]Jordi Condal Margarit is with the department of mechanical engineering, Polytechnic University of Catalonia (UPC).

Some small-scale SPAs have been developed for flexible and deformable actuations. In [12], the authors developed a very thin semi-rigid bending actuator using a similar actuation method, a bubble inflation. This actuator is designed for bending surfaces to obtain large flexible areas with multi DoF, other interesting work in micro scale silicone working is [13], in which the authors developed a micro valves made out of RTV silicone rubber through micro molding process. The thickness of the valves are 0.2 - 0.3 *mm* with 2 *mm* of diameter. A comparable work result to this paper are the papers [14], [15] in which a soft actuator is used to create a flexible array with multiple actuation points. In this case an electro-mechanical transduction of a two parallel plate capacitor is used to generate the motion. The proposed actuator is based on the stacked layer structure which comes from the Robogami platform [16]. It allows SPA-skin to be thin, highly customizable, adaptable to all surfaces and it can cover large areas with multiple actuation points.

Unlike electrically-driven actuators, it is rare to find elaborate works by using SPAs, because there are only a few feasible sensors that can measure the shape of SPA. SPA's complex properties, such as nonlinearity and instability, make it difficult to control. In [17], Yi *et al.* presented the SPAs behaviors, such as the force and the displacement of the SPA with respect to the pressure of compressed air. It could be used for the open-loop control of a soft pneumatic actuator. However, the SPA should have a close-loop control system to guarantee the precise motions of SPA. The size of micro scale or ultra thin SPAs varies in the fabrication process. Therefore, SPA needs embedded sensors not only to measure the motion of the SPA for precise control but also to minimize the fabrication errors of the SPA. The Colobot [18], which was made for colonoscopy, is equipped with optical sensors to measure the distance between the robot and porcine intestine for collision avoidance. The control of the robot is operated under an open-loop control after setting up the forward kinematic of the actuator by manually measuring the length of the stretched actuator. As embedding the sensor on the top of the actuator, the change of the size of the SPA-skin can be measured. The PID control, which is one of the famous feedback control algorithm, was implemented in the system. Because of the feedback control, SPA-skin can be applied to a flexible braille, a robot skin and a vibrotactile display which need sophisticate movements as well as flexibility

In this paper, we propose a novel SPA-skin which is capable of actuation with a thin flexible structure and precise manipulation by embedding flex sensors. Any kind of actuators, especially SPAs, that need to cover a large area

978-1-4799-6934-0/14/$31.00 ©2014 IEEE

with a distributed actuation and to have a sub-millimeter thickness is a great challenge. It would test limitations of the material as well as the mechanism, composing elements (*i.e.* actuators, sensors, circuits) and the integration. It requires a flexible actuator that can cover any kind of surfaces and embedded sensors. For the interactivity between an actuator and environment, there are two criteria: the thickness ($<$ 1 mm) and Young's modulus ($<$ 0.1 GPa) of an actuator. Therefore, the SPA-skin can be a solution to meet with the criteria in terms of design.

This paper is organized as follows. The design of the SPA-skin will be illustrated in Section II along with the comparison of compare several commercial sensors to embed into the SPA-skin. Section III shows the characterization of SPA-skin in details. Section IV implements a feedback control algorithm for the SPA and the experimental results. Section V concludes this work with the future directions.

II. DESIGN AND FABRICATION OF THE SPA-SKIN

In this section, we present the design of SPA-skin as a flexible and thin distributed actuator. Three commerically available bending sensors are exam to find the most suitable sensor for the embeddment in the designed SPA-skin.

A. Design of the SPA-skin

The structure of the proposed SPA-skin, consisting of three layers, is shown in Fig. 3. The multiple layers structure is based on the origamis concept [16] in which actuator is constituted by different function of layers. This structure allows the actuator to have a flexibility a minimum volume at the same time. These characteristics make the actuator easily adapt to any surface with a very low weight (only 0.22 g/cm^2).

The base layer in the SPA-skin is made of flexible fabric impregnated in cured silicone rubber. The function of this layer is to block the inflation by using inextensibility of the fabric. The middle layer is the mask to make a very thin air chamber inside and it goes superposed on the base layer. The function of this layer is to avoid the union between layers 1 and 3 on the mask. The upper layer is the cover layer and it is made of a very thin silicone rubber surface (0.3 mm). Layers 1 and 3 are bonded together and the air can flow along the internal corridors of the mask. This assembly is able to produce single displacement on the top of each actuation point.

A variant design of SPA-skin, called as full sphere SPA-skin is also developed. The full sphere SPA-skin is made by replacing the unstretchable layer of the SPA-skin (semi sphere SPA-skin) to a stretchable layer Fig. 2. With this modification it is possible to obtain an actuator with double side inflation. This is an advantage because both sides can be used as an actuation points to obtain large deformation or to sense the motion in one side and to actuate in the other side. In this case the fabrication method is similar to the first variant of the actuator but the mask is sandwiched with two different layers of silicone rubber. The two layers are bonded together except for the mask.

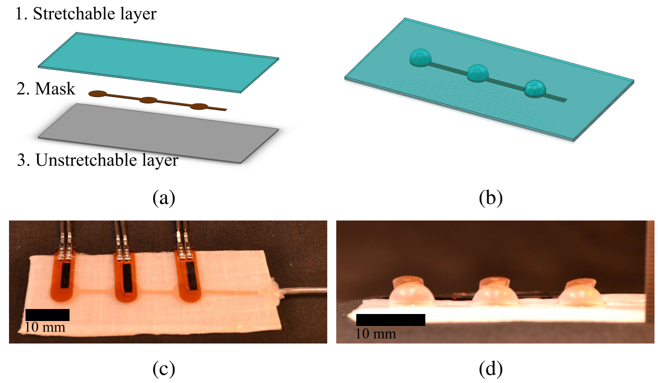


Fig. 1. The SPA-skin with three actuation points. Component layers (1: stretchable layer with Dragon Skin 30, 2: mask layer with polypropylene, 3: unstretchable layer with fabric) (a), illustration of all three actuation points activated (b), a top view of the prototype of a SPA-skin with embedded sensors (c), a side view of an inflated SPA-skin prototype (d).

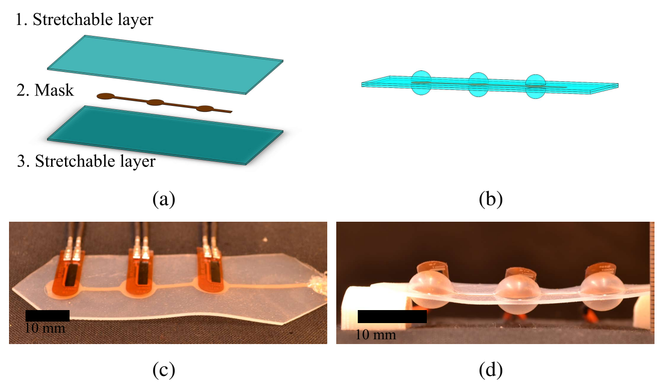


Fig. 2. Although very similar to Fig.1, Figure 2 presents difference in mode of actuation through a choice of the layer material.

The SPA-skin is operated by compressed air which makes the chambers of the actuator inflate as going through narrow corridors. In these parts the air inflates the chambers and the silicone rubber covers, as a membrane, expands. The advantages of SPA-skin is available to distribute lots of actuation points in one row with one single source of pressure and it is possible to cover large areas with multiple actuation points. The actuator allows the possibility to control each actuation point separately with multiple pressure sources.

B. Fabrication process

Figure 3 refers to the fabrication method of SPA-skin. The first step is obtaining an unstretchable layer. It is necessary to spread silicone rubber on the top of an unstretchable, flexible and porous material (ex. fabric) and it is distributed in an uniform way. After the silicone rubber is cured, the mask is located on the unstretchable layer. Silicone rubber is dropped on the two layers while a spin coater is rotating. Finally an air-tube is connected with the finished actuator. In Fig. 4, another stretchable layer is needed instead of unstretchable layer for the variant of SPA-skin, the full-sphere actuator. In both cases the same spin coater program is used. For the first 3 s the rotating speed goes up from 0 to 1200 rpm, keep for

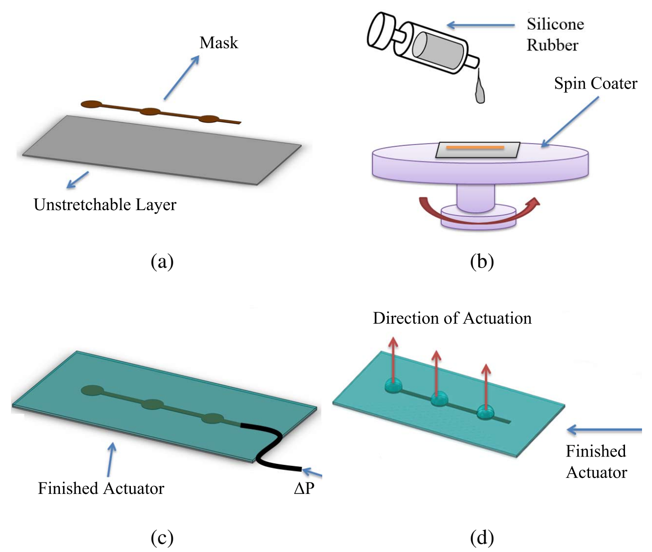


Fig. 3. Fabrication process for a single-sided SPA-skin. A mask is put on an unstretchable layer (a), the silicone is spun on the unstretchable layer to obtain a thin cover layer on a rotating spin coater (b), an air-tube is connected with the finished actuator (c), synopsis of the behavior of the SPA-skin (d).

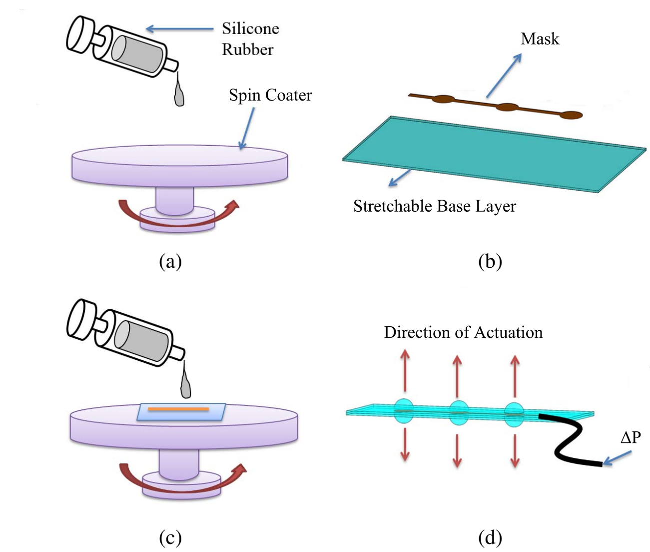


Fig. 4. Fabrication process for a double-sided SPA-skin (full sphere). The silicone is spun on the spin coater (a), the mask is superposed on the thin silicone layer (b), a new silicone layer is spun on the stretchable layer and mask (c), synopsis of the behavior of the SPA-skin (d).

3 s, and then come back from 1200 rpm to 0 in 3 s. The quantity of silicone rubber is approximately 10 ml. With this recipe, 0.3 *mm* thikness layer are obtained.

C. Component selection: Silicone rubber

The properties of the silicone greatly influence on the behavior of SPA-skin when it is actuating. Four types of silicone, which are widely used for making SPA, have been tested in this section.

Two important aspects in the selection of silicones are to make an appropriate inflation size and to avoid the delamination. The delamination effect happens when the base layer and the cover layer start to disengage one from the other. Normally it happens near the intersection of the mask because the stress in the area is much higher than other area. According to this characteristic, a less sensitive silicone in terms of deformation, is required. Dragon Skin 30 was chosen as the most appropriate silicone rubber.

TABLE I

SILICONE MECHANICAL PROPRIETIES (ASTM D-412) [19]

Material type	Ultimate tensile strength	100% Modulus	Maximum strength
EcoFlex 10	827.4 kPa	55.2 kPa	800%
EcoFlex 30	1379 kPa	68.9 kPa	900%
DragonSkin 10	3275 kPa	151.7 kPa	1000%
DragonSikin 30	3447.4 kPa	592.9 kPa	364%

D. Component selection: flexible sensors

There are two criteria in terms of choosing the sensor for the SPA-skin; size and response. First of all, it is necessary a sensor with less than 0.4 *mm* of thickness to guarantee that the actuator does not overpass the 1 *mm* thickness. The sensor size should match with the actuator size, which means around 20 *mm* length and around 1 *mm* width as maximum. The second reason is the response of the sensor. Logically, the most interesting response will be when it follows as near and smooth as possible the real motion of the actuator. Another important characteristic is that a static sensor is more recomendable than a dynaminc one because the static sensor provides constantly information about the position and the external forces.

One evaluated option for embed the senor in the actuator was the piezo film [20]. The advantage of this sensor is that can work at the same time as sensor and actuator and it have a very fast response Fig. 6 (b). The inconvenient is that it is a dynamic sensor and it only can give information when the actuator is moving and not when it is static. The sizes of the selected piezo film are 41 x 12 x 0.04 *mm*. The other option is the sensor Flexpoint Bend Sensor Fig. 6 (a) [21]. This sensor accomplishes all the requirements that the actuator needs, it is static sensor and the size is similar. The sizes of the sensor are 25.4 x 7.1 x 0.125 *mm*. Other analyzed sensor is the Two-Directional Bi-Flex Sensor Fig. 6 (c) [22] which is similar to the Flexpoint. The strength is that this is more easily customizable than Flexpoint.

III. CHARACTERIZATION OF SPA-SKIN

Four different sizes of the mask of SPA-skin will be characterized in Section III: $\phi 4$, $\phi 6$, $\phi 8$ and $\phi 10$ *mm*. The depth of the airway in mask is 1.5 *mm* for all the cases and it affects, with the air flow, the inflation speed of the actuator. The minimum depth of the corridor, which guarantees uniform air flow is 1 *mm* for Dragon skin 30. The rounding, which decreases the stress in the intersecting point between a corridor and an air-chambers, is $\phi 0.5$ mm. The thickness of the silicone rubber layer (i.e., stretchable

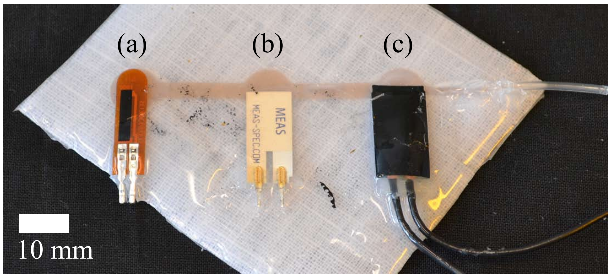


Fig. 5. Three flexible sensors embedded in a three actuation points of the SPA-skin. Flexpoint sensor (a), piezo electric sensor and (b), bi-directional bendable sensor (c).

layer) (and the thickness of the mask are 0.03 *mm* and 0.05 *mm* respectively. The thickness of the unstretchable layer is 0.6 *mm*. The total mass of the SPA-skin is 0.22 g/cm^2.

A. Actuator specifications

In this part the different values that define the actuator are exposed for the four different sizes. The inflation speed is in function of the input pressure and the type of silicone rubber. For the different diameter sizes and with a 20 kPa step function input the speeds are; size $\phi 4$ *mm* 1.43 mm/s, for size $\phi 6$ *mm* 12.4 mm/s, for $\phi 8$ *mm* 15.84 mm/s and for $\phi 10$ *mm* 22 mm/s.

It is difficult to solve the transformation of the end-link in the SPA-skin, unlike in the traditional hard robot [18]. Since the silicone-based actuator is regarded as a high DoF actuator and a soft robot, it is inappropriate to use the robotic conventions which are based on rigid body dynamics. Therefore, we propose the forward kinematics formula for the SPA-skin.

The sensor is under the bottom of the full-sphere SPA-skinand on the top of the semi-sphere, respectively. The change of the sphere size affects the variation of the deflection of the sensor. The deflection of the actuator is proportional to the resistance of the sensor. Experimentally, we tried to find the relation between the height of the actuator and the deflection of the sensor. We captur the motions of the actuator through video and measured the end-point of the actuator with visual markers by a motion capture program recording the motion. The voltage, instead of the resistance of the actuator, is measured with an Operational-AMP (LN324n, TexasInstrument^{TM}). The deflection and voltage are proportional to the pressure of the chamber of the actuator. The experimental results show the nonlinearity in the elongation of the actuator.

B. Actuator blocked force mesurements

The actuator behavior depends most on the input pressure that enters the actuators. Apart from this, other geometrical and dimensional characteristics affect the actuation behavior. One of them is the diameter of the actuation points, which are the size of the circles in the mask, the thickness of the cover layer and the geometry of the mask. In this characterization, only the pressure and the size of the mask are studied. The

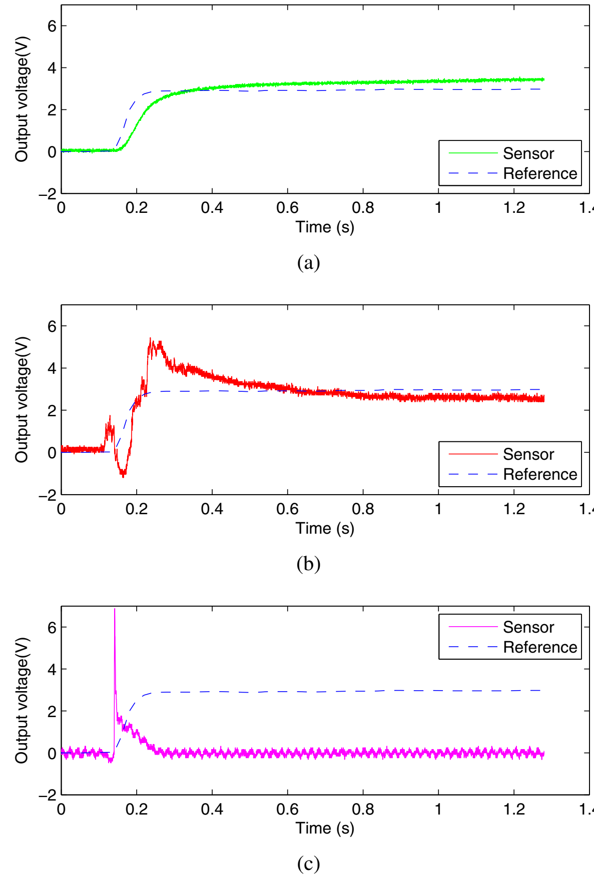


Fig. 6. Flexible sensor sensitivity comparisons when the input is . Behavior of the bi-directional bendable sensor (a), behavior of the flexpoint senso (b) and behavior of the piezo electric sensor (c).

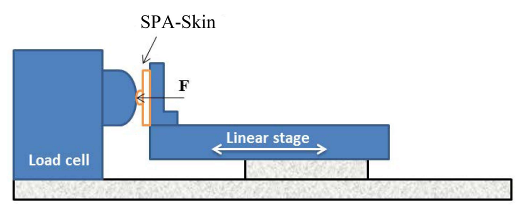


Fig. 7. Experimental setup for measuring blocked force of the SPA-skin's single actuation point.

dimensional values are in the Section II-A. We implement the characterization for displacement and block force of SPA-skin with respect to input pressure: 5, 10, 15 and 20 kPa. The setup consists of a bedplate on which there are the load cell (Force Transducter Fnom = 100N), fixed in one side, and in the other side the linear stage which can move to zoom on or out the actuator respect to the load cell. Then the assembly linear stage and actuator is moved until it contacts to the load cell. The actuation point pulls on the load cell when a certain pressure enters inside the actuator and, consequently, the load cell measures the force in this singular point. Figure. 7 shows the experimental setup

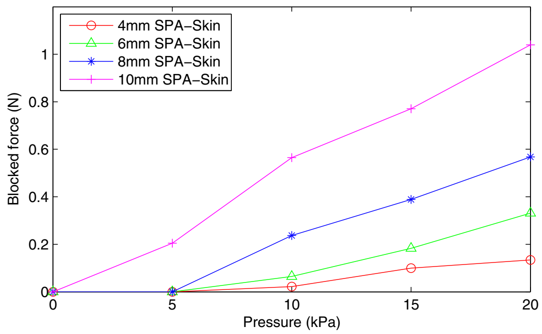


Fig. 8. Blocked force output of the developed SPA-skinin relation to the pressure input.

C. Displacement mesurements

To ensure the displacement a tracking program was used. After taking the video with a motion analysis program (Tracker™), it was possible to obtain the displacement of the top of the actuation point.

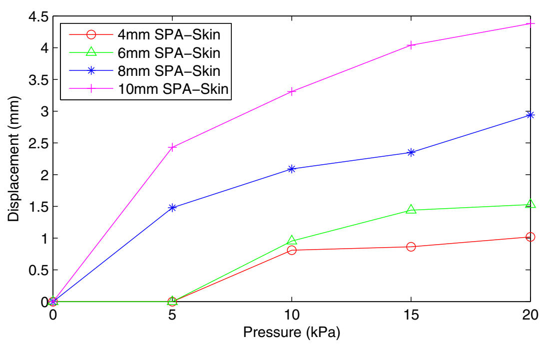
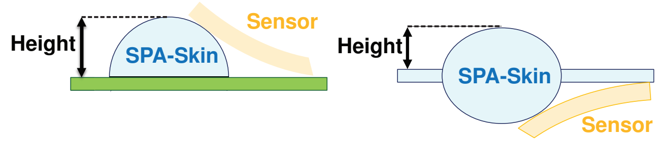


Fig. 9. This graph shows the relationship between pressure and displacement. The displacement change of the SPA-skinis proportional to the input pressure and the size of the chamber of SPA-skin.

IV. SPA-skin Control

The purpose of feedback control for SPA-skin is to maintain the constant dimensions of SPA-skin in Fig. 10. Most control methods for SPAs have been presented with the assumption that the elongation of the actuator is proportional to the input pressure [23]. However, soft materials, such as elastomer, have an instability when a threshold of the size of inflation is exceeded [24]. The required input pressure for inflating a SPA-skin decreases as a function of strain because the rate of inflation is greater than the rate of decrease of the internal pressure. Therefore, feedback control is required for the SPA-skin to control precisely.

We implemented an experimental setup to demonstrate the control algorithms: we used a SMC™ regulator (ITV1011-21F1N) and solenoid valves (VQ100) to adjust the pressure of the chamber of the actuator, a cDAQ board (NI cDAQ-9178) for the measuring signal, and a transformer to get a constant 12V, 5V DC voltage.



(a) (b)

Fig. 10. The purpose of the control loop is to adjust the height of the SPA-skin by receiving the cuvature information from the sensor (a) schematic diagram of SPA-skin (b) schematic diagram of full sphere SPA-skin

A. PID control to maintain the height of SPA-skin

To reach or to maintain a specific height of SPA-skin, it should be operating under a close-loop control. We implement the PID control by receiving feedback from the embedded sensor. In Fig. 11, the settling time of the close-loop control is much smaller than the settling time of the open-loop. The height of the SPA-skin with the open loop control keeps increasing after it reached the desired position. Furthermore, when an external force is applied to SPA-skin in Fig. 12, the open-loop can not return to the original position because of *Mullins effect* [25]. The close-loop control is robust considering various effects of the polymer material behaviors. At current stage, the presented PID control already displays sufficient controllability of the prototype but we will explore further control methods that would involve damping effect of the sensors in the immediate future.

B. Detecting external force through the sensor

We present the force detection method through the sensors in the SPA-skin. As an external force is applied to SPA-skin, the feedback control system may malfunction because the signal from the sensor does not guarantee the height of SPA-skin. In other words, the signal from the sensor of SPA-skin is affected by an external force as well as the internal pressure. Because an external force prevents from inflation of the SPA-skin, the signal shows the state. For example, when touch the SPA-skin, the resistance of the sensor, changes dramatically. Even though this is not compatible with the close loop control simultaneously as there is only a single, we can use this phenomenon to detect an external force.

Two kinds of SPA-skin were proposed in Section II. To measure the force, the sensors of SPA-skin and the full sphere SPA-skin are located on the top and at the bottom of the actuator respectively in Fig 10. The applied force to the SPA-skin can be calculated from the change of the height of the SPA-skin. The Flexpoint™ sensor is not affected by force even though it is based on Carbon ink. SMC™ regulator has own feedback control loop that makes the internal pressure keep constant against disturbances. However, it is still possible to derive of the external force from comparing the signal from the sensor and an internal pressure of SPA-skin. When an external force applied to the actuator, the signal from a sensor is changed but the internal pressure of the actuator is still same. The weight on the top the SPA-skin causes to reduce the height of the actuator. In Fig. 12, sensor reading is related with the reduced height and the internal pressure of the SPA-skin. The estimated height are bigger and smaller in SPA-skin, full sphere SPA-skin respectively. The force detection function can be applied to flexible braille or vibrotactile feedback system.

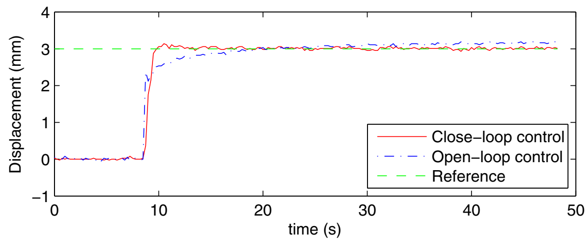


Fig. 11. SPA-skin step response to reach the desired position, 0.5 *mm*. Red line and blue dash line represent the SPA-skin with the close-loop control and the open-loop control respectively. The close-loop control is much faster than the open loop control until reaching the desired position. Furthermore, the SPA-skin with open-loop control keep increasing despite of under same pressure.

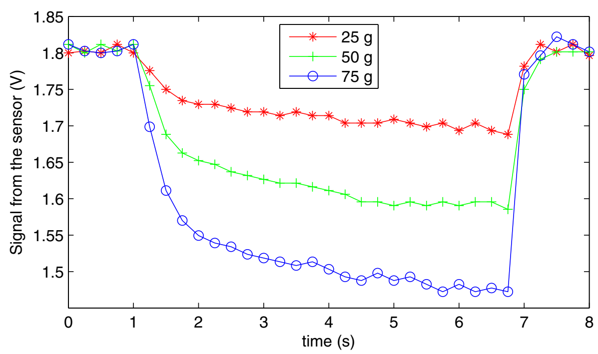


Fig. 12. Sensor response of the SPA-skin with respect to three different weights on the top. The number of weight is inversely proportion to the height of the SPA-skin.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we present the novel design, characterization, and the control of SPA-skin. In the thin SPA-skin, we embedded Flexpoint bending sensors to examine the controllability of the presented prototype via PID controller. Due to the strong non-linearity inherent to the material, we used experimentally driven parameters to set the control gain while making some geometric assumptions that proved to be favorable at the current state. As a both input and output device, our preliminary test results show its potential applications in flexible braille or vibro-tactile feedback system for wrist rehabilitation. In the near future, our two proposed algorithms will work in a framework with an adaptable customized stretchable sensors.

VI. ACKNOWLEDGMENT

This work was supported by the Swiss National Centre for Competence in Research (NCCR) Robotics fund. The authors would like to thank Merve Acer for providing valuable advice on sensors.

REFERENCES

[1] D. Trivedi, C.D. Rahn, W.M. Kier, and I.D. Walker, “Soft robotics: Biology inspiration, state of the art and future research,” *Applied Bionics and Biomechanics*, vol. 5(1), pp. 99-117, 2008.

[2] F. Llievski, A.D. Mazzeo, R.F. Shepherd, X. Chen, and G.M. Whitesides, “Soft robotics for chemists,”*Angew Chem Int. Ed Engl*, vol. 123(8), pp. 1930-1935, 2011.

[3] Y. Sun, Y. S. Song, and J. Paik, “Soft Pneumatic Actuators with Various Actuation Mechanisms,” in *the 7th World Congress on Biomimetics, Artificial Muscles and Nano-Bio (BAMN)*, Jeju Island, Korea, 2013.

[4] S. Kim, C. Laschi, and B. Trimmer. ”Soft robotics: a bioinspired evolution in robotics,” *Trends in biotechnology* (2013).

[5] G. Chen, M.T. Pham, and T. Redarce, “Development and kinematic analysis of a silicone-rubber bending tip for colonoscopy,” *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 168-173, 2006.

[6] R. Deimel and O. Brock, “A Compliant Hand Based on a Novel Pneumatic Actuator,” in *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA)*, pp. 2039-2045, 2009.

[7] R. V. Martinez, J. L. Branch, C. R. Fish, L. Jin, R. F. Shepherd, R. M. D. Nunes, Z. Suo, and G. M. Whitesides, “Robotic Tentacles with Three-Dimensional Mobility Based on Flexible Elastomers,” *Advanced Materials*, vol. 25, pp. 205-212, 2013.

[8] S. Wakimoto, K. Ogura, K. Suzumori, and Y. Nishioka, “Miniature soft hand with curling rubber pneumatic actuators,” in *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA)*, pp. 556-561, 2009.

[9] Y. Song, Y. Sun, R. van den Brand, J. von Zitzewitz, S. Micera, G. Courtine, and J. Paik, “Soft robot for gait rehabilitation of spinalized rodents,’ ’ *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 971-976. IEEE, 2013.

[10] T. Ranzani, M. Cianchetti, G. Gerboni, I. De Falco, G. Petroni, and A. Menciassi, “A modular soft manipulator with variable stiffness,” in *3rd joint workshop on New Technologies for Computer/Robot Assisted Surgery*, 2013.

[11] R.F. Shepherd, F. Ilievski, W. Choi, S.A. Morin, A.A. Stokes, A.D. Mazzeo, X. Chen, M. Wang, and George M. Whitesides, “Multigait soft robot,” *Proceedings of the National Academy of Sciences*, 108(51), pp: 20400-20403, 2011.

[12] S. Konishi, F. Kawai and P.Cusin,“ Thin flexible end-effector using pneumatic balloon actuator,” in *Sensors and Actuators A: Physical*, 89(1-2), 28-35, 2001.

[13] Y. Uohashi, K. Suzumori and H. Taniguchi, “ Fabrication and evaluation of various types of micro one-way valves through micro rubber molding process,” in *Journal of mechanical science and technology*, vol. 24(1), pp. 219-222, 2010.

[14] S. Lee, K. Jung, J. Koo, S. Lee, H. Choi, J. Jeon, J. Nam and H. Choi,“ Braille display device using soft actuator,” in *Proc. of SPIE*, vol. 5385, pp. 369, 2004.

[15] I. Koo, K. Jung, J. Koo, Y. Lee and H. R. Choi, “Wearable tactile display based on soft actuator,” in *Robotics and Automation, ICRA 2006, Proceedings 2006 IEEE International Conference*, pp. 2220-2225, 2006.

[16] A. Firouzeh and J. Paik, “Robogami: a low-profile soft robot with integrated sensors and actuators,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 4937-4944, 2013.

[17] Y. Sun, Y. S. Song, and J. Paik, “Characterization of Silicone Rubber Based Soft Pneumatic Actuator,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 4446-4453, 2013.

[18] G. Chen, M.T. Pham and T. Redarce, “Sensor-based guidance control of a continuum robot for a semi-autonomous colonoscopy,” in *Robotics and autonomous systems*, vol. 57(6), pp. 712-722, 2009.

[19] Smooth-On, http://www.smooth-on.com/.

[20] Piezo Film Sensors Measurement Specialties, http://www.meas-spec.com/piezo-film-sensors.aspx

[21] Flexpoint, http://www.flexpoint.com/.

[22] Bi-Flex Sensors-IMAGES Scientific Instruments, http://www.imagesco.com/sensors/flex-sensor.html

[23] F. Thomann, M. Betemps, and T. Redarce, “The development of a bendable colonoscopic tip,” in *Proc. IEEE Int. Conf. on Robotics and Automation (ICRA)*, vol. 1, pp. 658-663, 2003.

[24] A.N. Gent, “Elastic Instabilities in Rubber,” *International Journal of Non-Linear Mechanics*, vol. 40, pp. 165-175, 2005.

[25] L. Mullins, “Softening of rubber by deformation,” Rubber Chemistry and Technology, vol. 42(1), pp. 339-362, 1969.