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Thin Soft Pneumatic Actuator Based on a Novel Fabrication Technique

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Abstract— **This paper presents a novel fabrication method for constructing thin soft pneumatic actuators. The method is based on building up thin layers of elastomeric material with embedded strain-limiting and mask layers using a bespoke film applicator. This enables the fabrication of millimetre-scale soft actuators with complex integrated masks and/or strain-limiting layers, as demonstrated in a series of proof of concept prototypes. The prototype actuators can be cut into a desired shape via laser cutting this laminated sheet. This paper show the feasibility of the fabrication method and the value of its use in creating thin soft pneumatic actuators for application in soft robotics. The technique can be further developed to fabricate multi-material composite soft actuators which are thin, compact, flexible and stretchable.**

I. INTRODUCTION

There have been great advances in the field of soft robotics since its inception, founded to bridge the gap between nature and the state of the art 'rigid' robotic systems of the day. There is increasing demand for soft robotic technology due to factors including the innate compliance, safety, and adaptability which such systems possess. To date soft robotic systems have typically operated at centimeter or larger scales, largely limited by the fabrication processes involved in their manufacture. However, there is growing demand for smaller, more precise and more dexterous soft robotic systems which can address challenges in diverse areas including healthcare and search and rescue [1-3]. Thus, the development of new high-precision fabrication techniques is crucial to support the advancement and expansion of soft robotics.

Since its inception, soft robotic fabrication has seen a shift from conventional 'moulding and casting' methods to explore a range of rapid prototyping techniques including 3D printing [4-6], soft lithography [7-9], shape deposition manufacturing [10, 11], and combinative techniques [12-17]. These techniques have all been exploited to build soft robotic actuators and inflatable surfaces [18-22]. Soft actuators such as PneuNet [23] and FPAM [24] have inspired variants of soft pneumatic actuator (SPA)'s designs over the years, all of which use a form of moulding or casting in their fabrication process. Attempts have been made to build small SPAs based on 3D printed moulds, however, despite the feasibility, due to design and geometrical constraints of moulding techniques, the ability of these actuators to operate in application with narrow and limited space are somewhat limited [3, 25, 26]. Moreover, moulding fabrication techniques are inherently limited in the geometries they can produce which consequently limits the functionality of the actuators they produce.

In order to address the shortcomings of conventional SPAs, there is a need for more flexible fabrication methods that can easily produce soft actuators at small scales with features and functionalities that can be easily designed.

In this paper, we describe a novel Thin Soft Layered Composition (tSLC) fabrication technique to develop thin (< 1 mm) soft pneumatic actuators (tSLA) with precise sub-mm features. The technique derives from laminating and stacking thin precision-cut laminar materials which can include soft elastomers as inflatable layers, strain-limiting layers, and mask layers. The regions covered by the mask layer (between strain-limiting layer and inflatable layers) define inflatable zero volume cavities that can be selectively actuated through fluid inlets. This fabrication method enables the creation of complex, articulated mechanisms with submillimetre scale mechanical features with a range of potential applications in soft robotic research.

The remainder of the study is organised as follows: Sec. II describes the conceptual design for the tSLA and its production using our new tSLC fabrication method. The characterisation and test results of the actuator is then discussed in Sec. III. Followed by, a discussion of the fabrication technique and conclusion in Sec. IV and V respectively.

II. ACTUATOR DESIGN AND FABRICATION METHOD

Conceptual Design

Our proposed thin soft pneumatic actuator (tSLA) consists of thin soft elastomeric layers, strain-limiting layers, and mask layers stacked on top of each other to form a compound system, as shown in Fig. 1(a) and 1(b). Portions of the strain-limiting layer and the elastomeric layer can be selectively adhered to each other based on the mask layer features. This forms an inflatable structure with zero-volume chambers. The elastomeric material layers enable expansion of the inflatable cavities and channels as well as adhesion between layers when applied in a pre-polymer form. The stiffness of this layer must be less than that of the strain-limiting layer such that it bends or deforms more readily compared to the strain-limiting layer.

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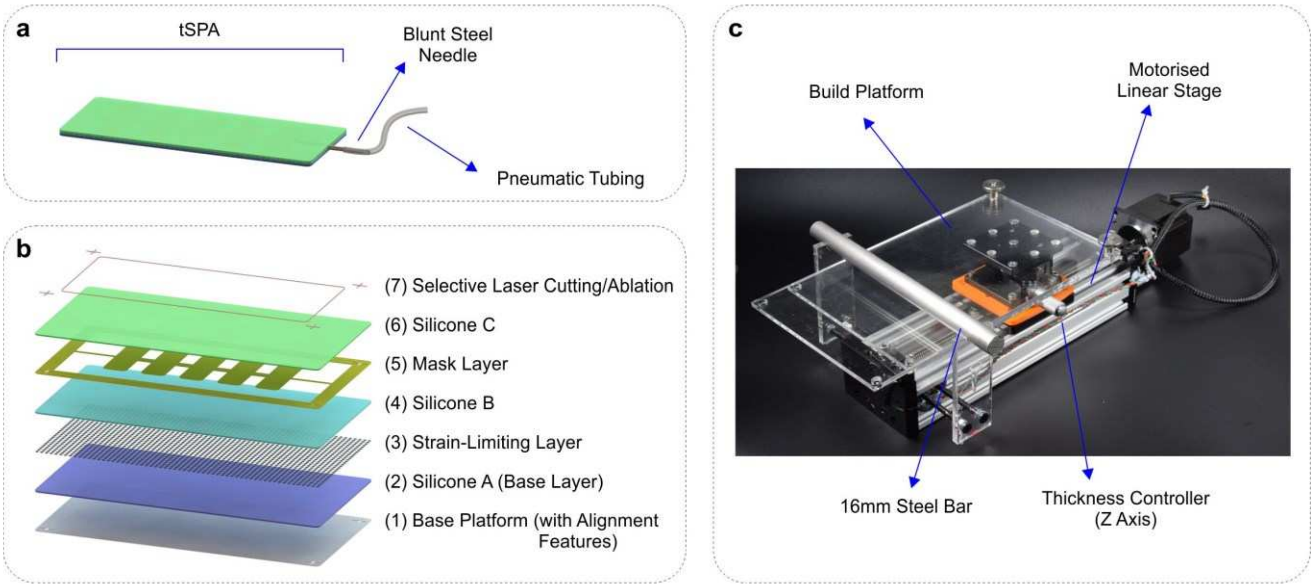

Figure 1. (a) Conceptual design for the tSLA, (b) Schematic diagram of the tSLC fabrication steps to create tSLA (orthogonal view). This includes base platform with alignments features, elastic layers (i.e. silicone), mask layer produced via laser cutting, and final selective laser cutting to pattern and/or separating the tSAP from the base platform sheet, (c) Bespoke thin film applicator to apply thin and uniform prepolymer silicone.

A stiffer elastomer or inextensible material (i.e. fabric, paper, PET film) can be used for strain-limiting layers. This layer acts to resist various types of strains in one or multi directions until its yield strength is reached. Upon actuation, expansion of the inflatable layer is directed by the strain-limiting layer, causing a bending motion or resultant force for actuation.

Using this concept, the stiffness, overall thickness, inflation profile and geometry of the soft actuator can be manipulated layer by layer, with the selection of appropriate materials and profiles and consideration of their configuration relative to each other. This can then be utilised to develop tSLAs with a range of pre-programmed behaviours and geometries.

Fabrication Technique

The conceptual tSLA design drove the development of our tSLC fabrication method which aims to exploit a combination of thin laminar structures, created here using a bespoke film applicator – as shown in Fig. 1(c), which can be precisely cut or etched using a laser-cutter. The applicator consists of a linear actuating stage (C-Beam® Linear Actuator, Open Build) of 250 mm travel distance with a manual vertical stage (MAZ-40-10 Z-axis Vertical Stage, Optics Focus Solutions) to control the height of the applicator platform made of extruded acrylic (W: 250 mm, L: 150 mm). A metal rod of 16 mm Ø is mounted at a set height of 10 mm from the base of the rod to the applicator platform. The translational stage moves the film platform relative to the rod at between 100 and 500 mm/s. The vertical stage is then manually calibrated to adjust rod-plate separation and thus produce films sheets of desired thicknesses ranging from 0.1 mm to 1 mm.

The tSLC fabrication process, shown in Fig. 2(b), is as follows; (i) the applicator is set to the desired layer thickness while pre-polymer silicone is poured onto the centre of the platform. (ii) The platform is then actuated at a desired set speed; spreading the silicone across the platform to produce the desired thickness. (iii) Once the silicone has spread, the platform is then removed and placed into an oven at 45°C to cure for 10~15 minutes depending on the type of silicone. (iv) Strain-limiting materials (i.e fabric or pre-polymer silicone) or laser cut masks layers are then added to the layer before and/or after the silicone has been cured. (v) Further layers of silicone or embedded material are introduced by repeating stages (i)-(iv) based on the desired layer configuration. Once completed, the composite structure is aligned onto a backing paper, using the alignment features, and placed into a laser cutter (Universal Laser Systems-VLS 3.50, 50W Laser Cutter) to cut out the desired shape, as shown in Fig. 2(a). The fabricated actuators are then cleaned (using isopropanol), integrated with pneumatic airlines and ready to be tested.

The selective laser cutting process can be used not only to cut the tSLA and separate it from the base build platform, but also to cut individual layers and/or pattern them to produce desirable features for the tSLA. The profile of these patterns can be controlled in Z direction by adjusting power and speed settings of the laser beam. Same alignment features are utilised to align the layer on the laser's cutting platform. The layer must be cleaned by an airgun and then a sonicator to remove any debris and soot from the layer. This will provide a clean surface and make sure good bonds can be created when other layers are added in the tSLC process [27, 28].

Fabrication of tSLA

A range of prototype tSLAs were developed to evaluate their performance and the characteristics and efficacy of the underlying fabrication method.

As illustrated in Fig 1(a) and 1(b), a layer-by-layer schematic was first designed to determine the sequential process for the actuator fabrication. The fabrication of each soft actuator is then as follows: (i). the applicator is configured to produce the desired layer thickness. Pre-polymer silicone is prepared for all elastomeric layers, in this instance using Ecoflec 50 (Smooth-On Inc., USA) mixed at 2000 rpm for 90 s (ARE-310, Thinky Inc., Japan). Defoaming of the mixture was performed at 2200 rpm for the same time period. After mixing, the mixture was poured onto the platform and spread across using the film applicator to form a silicone sheet of 0.4 mm. A fabric mesh with 0.1 mm thickness (Soft 'n Sheer stabiliser, Sulky of America Inc.) is then placed on top of the pre-polymer silicone layer to embed the fabric as a strain-limiting layer. (ii). The platform is then removed from the stage and placed into the oven at 45°C for 15 minutes. This process speeds the curing of silicone and control the thickness of the film, while other elastomeric material may require longer curing times. (iii). Once the first layer has been cured, the platform is adjusted to compensate to the new height and another layer of 0.4 mm thick Ecoflex 50 is applied and cured in the oven. (iv). A mask layer of 0.1 mm thickness (Paper Solvy Water Soluble Stabiliser, Sulky of America Inc) is laser cut to the shape of the zero-volume cavity and then manually aligned on top of the cured layer of silicone. This is then followed by an application of a 1.5 mm layer of silicone to encapsulate the mask layer. (v). After the final layer of silicone is cured, the sheet is then removed from the build platform onto an alignment sheet for laser cutting. The mask layers are made of water-soluble paper and are thus easily removed from the designed actuator by flushing, leaving a zero volume chamber for pneumatic inflation.

III. CHARACTERISATION AND RESULTS

Experimental Design

Preliminary characterisation of the prototype tSLAs were performed to consider the effect of two key design parameters on the actuator behaviour; channel configuration and cavity width. As shown in Fig. 2(a) and 2 (b), based on preliminary work a nominal spacing between cavities was set at 5 mm width for two cavity width configurations of 5 mm and 3 mm. In addition, two channel configurations were designed to investigate the effect of placing pressure lines in different locations, while the total channel width (3 mm) remained constant between different configurations.

A custom experimental test rig, shown in Fig. 3, was developed to measure block force and bending angle of each tSLAs across a range of controlled input pressures (0 to 5 psi). For each test, the prototype actuators are inflated using a custom syringe-driver consisting of a linear stage (C-Beam® Linear Actuator, Open-Build) of 250 mm travel and a 50 ml syringe. An analogue absolute pressure transducer (30PSI SSC series absolute pressure transducer, HoneyWell, USA) was used to monitor the pressure applied to the actuator.

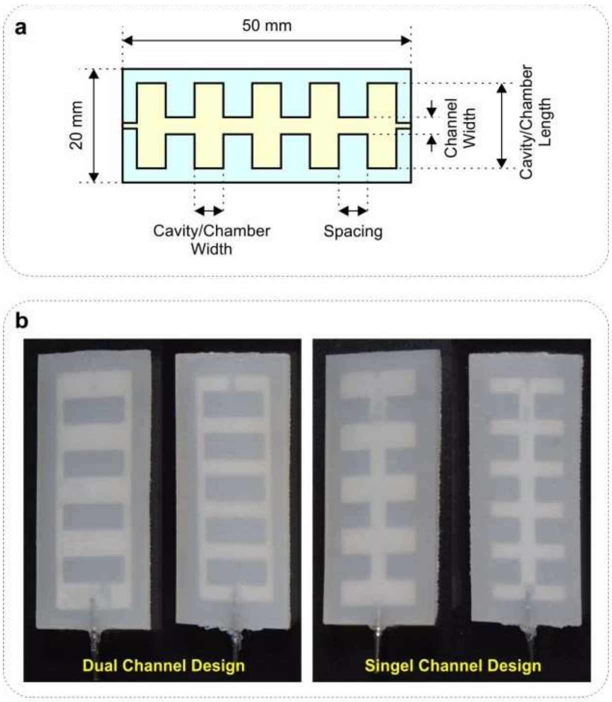

Figure 2. tSLA protoypes; (a) conceptual design and features, (b) fabricated tSLAs with different channel and cavity width configuration.

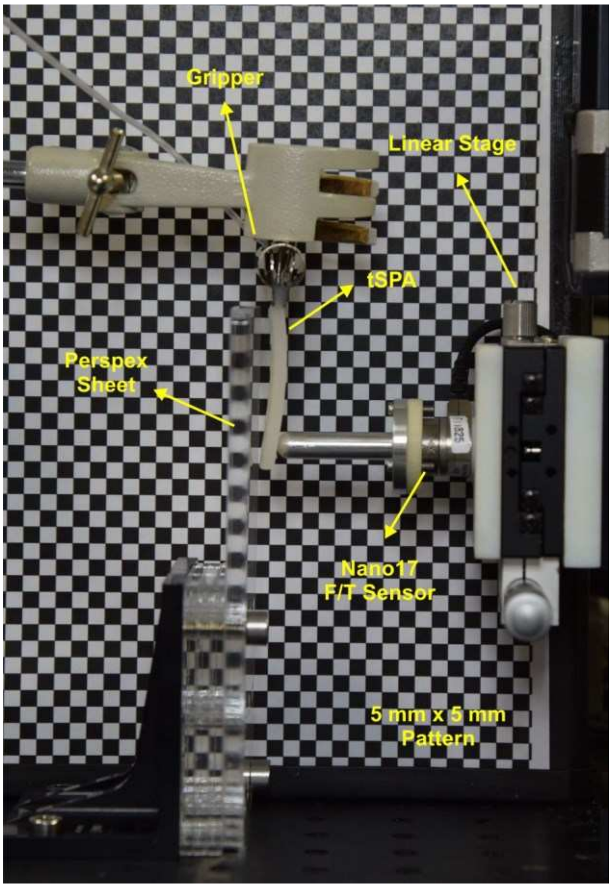

Figure 3. Experimental apparatus used to conduct block force and actuation angle experiments.

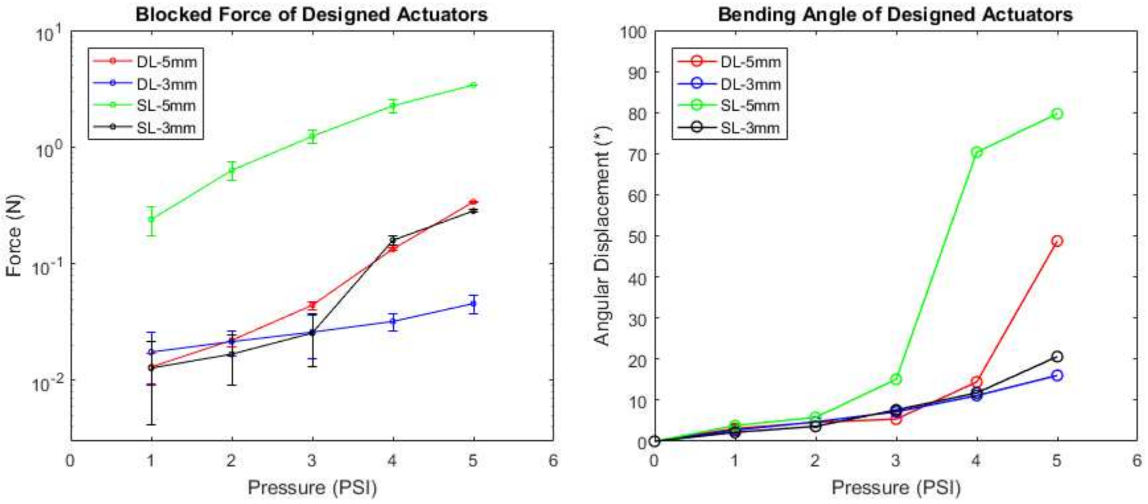

Figure 4. Results of the blocked force and tip bending angle response for the tSLAs at five static input pressures between 0 and 5 psi.

A 6-axis loadcell (Nano17, ATI Industrial Automation, USA) was used to measure the block force generated by the tSLAs. The actuator side surface was placed in contact with a rigid Perspex plate to minimise nonlinear effects due to bending. The pressure inside the actuator was then incrementally increased and normal force exerted by the tSLA's tip was recorded. Each experiment was repeated three times to assess accuracy and repeatability. A custom program was developed using LabVIEW (National Instruments, USA) to acquire the measurements from the loadcell and pressure transducer, while controlling the syringe pump at the set static input pressures.

The bending angle of the tSLAs at controlled input pressures were recorded by using a high definition camera (D5300, Nikon, Japan) along with a measurable calibrated backing pattern (5 mm × 5 mm grid). The technique allowed lens distortion issues to be addressed and measurement accuracy to be enhanced. Post processing of the pictures was performed using an open-source image analysis program (ImageJ Image Processing and Analysis in Java) in which the Cartesian X and Y coordinates of the actuator tip were tracked and the resultant total bending angle was calculated.

Results

The range of prototype actuators were evaluated using static pressure tests, where the actuator's blocked force and bending angle were measured. All tSLAs were subjected to static pressure between 0 and 5 psi at 1 psi increments and all completed these tests without failure.

The experimental results for the blocked force of the tSLAs are shown in Fig. 3(a). In all designs, the blocked force generated by the tSLA increases with input pressure. The actuator showing the best performance (5 mm chamber width, single channel) showed a maximum blocked force of 3.5 N at 5 psi static input pressure. The tSLAs with 5 mm chamber width obtained significantly higher blocked force output when compared to the narrower 3 mm chamber design across all input pressures.

As shown in Fig. 4(a) and Table 1, the channel design (single line in the centre or double lines on the sides) can have significant influence on force generation. From our results, the blocked force increased by 10 fold for the 5 mm chamber width in the single-line channel design when compared to the double-line.

The free response of the actuators shows that the tSLA bending angle increases with pressure across all designs as shown in Fig. 4(b) and Table 1. Similar to the blocked force experiment, the bending angle of the tip is significantly higher for the 5 mm chamber width design. The channel design is also influential, for the same cavity width, double lined configurations show lower bending. It was noted that there was expansion of the double channels at either side of the actuator which resisted the bending moment of the tSLA, hence

Table 1. Results of the blocked force and tip bending angle response for the tSLAs at five static input pressures between 0 and 5 psi.

tSLA Designs	**Blocked Force (N)**					**End Tip Angel (deg)**				
	1 psi	**2 psi**	**3 psi**	**4 psi**	**5 psi**	**1 psi**	**2 psi**	**3 psi**	**4 psi**	**5 psi**
SL – 3 mm	**0.0127**	**0.0168**	**0.0254**	**0.1586**	**0.2830**	**2.1890**	**3.6500**	**7.6480**	**11.7800**	**20.6160**
SL – 5 mm	**0.2390**	**0.6313**	**1.2340**	**2.2548**	**3.3974**	**3.8400**	**5.8300**	**15.0830**	**70.3470**	**79.6950**
DL – 3 mm	**0.0175**	**0.0215**	**0.0259**	**0.0320**	**0.0455**	**2.7440**	**4.7300**	**7.1930**	**11.1340**	**16.0420**
DL – 5 mm	**0.0130**	**0.0220**	**0.0441**	**0.1334**	**0.3381**	**3.1110**	**4.6280**	**5.4040**	**14.4450**	**48.7410**

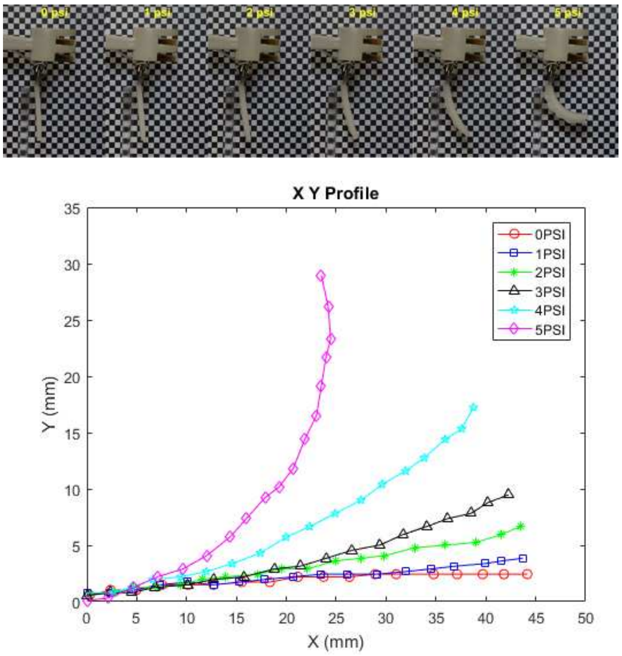

Figure 5. A prototype tSLA with 3 mm chamber width and single line channel design; (a) Side view of this actuator at 0 to 5 psi input pressure, (b) Calibrated X-Y profile of the actuator

constraining the bending of the actuator in comparison to a single channel configuration.

The sensitivity of the actuator's to input pressure exhibits a noticeable non-linear response. For input pressures up to approximately 3 psi, small changes of bending angle were observed per unit pressure change. A possible explanation is that, in this pressure regime, the tSLAs stiffens by first expanding against the strain-limiting constraint fabric layer. Beyond this point, small changes in input pressure generate far larger changes in bending angle and these effects are amplified based on the cavity width.

From these investigations we subjected the prototype tSLAs to additional testing to explore the bending characteristics across a range of pressures. The results for the 3 mm chamber width and single channel configurations are presented in Fig. 5 showing the Cartesian position of the actuator segments and corresponding images from which these measures were obtained. The non-linear response of the actuator across the pressure range is again evident in this response. For pressures up to 3 psi the actuator produces a near-linear response with low curvature. Beyond this, at 4 and 5 psi, there is a marked change in the form of the actuator, with higher curvature which increases toward the tip. Inspecting the images shown in Fig. 5(a) shows this is linked to expansion of the zero volume chambers and is a factor which could be controlled through manipulation of the constraint layer.

IV. DISCUSSION

In this study, we introduced a novel Thin Soft Layered Composition (tSLC) fabrication technique and demonstrated its capabilities through a series of proof of concept thin Soft Layered Actuators (tSLAs). The technique allows creation of thin laminar systems, ideally suited to actuators with zero-volume fluidic cavities but also applicable for different soft robotic devices with structural, actuation and sensing capabilities.

Using tSLC fabrication, the thickness of each layer can be carefully controlled using a film applicator (i.e. for prepolymer materials, paste) and/or by choosing a readily available film/sheet (i.e. polyvinylidene chloride – PVDC, polyethylene terephthalate – PET, Kevlar) which can be incorporated in to the tSLC fabrication process without additional resizing or preprocessing. Use of thin "two dimensional" layers also allows the use of laser cutting and ablation techniques for the creation of precise patterns and features in/on each layer. These design features of tSLC fabrication aid repeatability of the process and enable smaller features to be embedded within soft robotic systems, hence, offering the possibility of reducing the overall scale of soft systems. This provides the opportunity for mm scale soft systems with precise operation which can be readily tailored for application specific requirements.

This approach can be used to develop a multi-material composite soft actuator consisting of multiple actuation position/layers in which the entire actuator is thin, small, soft flexible and stretchable. The technique has produced a range of elastomeric sheets using Eco-Flex series and Dragon Skin series silicones (Smooth-On Inc.). In our early designs presented here, there is no constraint layer limiting the inflation profile of the top layer during actuation. In some cases, the cavity pressure may exceed the elastic layer's yield point. This can be controlled by adding an additional constraint layer (made of a stiffer material compared to that of the inflatable layer, e.g. stiffer silicone) on top of the inflatable layer (silicone C in Fig.1(b)). For small gaps (< 1 mm) between chambers/features, elastic layers start to delaminate at pressures above 5 psi due to failure of the bonding mechanism. Isopropanol can be used to clean the surface before application of another layer. This was used to produce a strong bond and stop the delamination of the layers. Using this technique, tSLAs of 0.5mm to 5mm actuators can be produced.

tSLAs, fabricated using tSLC technique, provide distinct advantages compared to comparable soft robotic actuators. The thin form factor of each layer allows the stacked combination of multiple layers, each bringing different functionalities (i.e. structural elements, sensing layers) without significantly increasing the thickness of the overall composite actuator. Thin soft robotic actuators are particularly interesting as they can be designed to form 3D shapes (or surfaces) from 2D structures when actuated [20]. Unlike other soft robotic actuators, their "2D" nature make tSLAs lightweight and portable, eliminating much of the material 'bulk' seen in pneuNet approaches.

V. CONCLUSION

A novel Thin Soft Layered Composition (tSLC) fabrication technique was proposed and used to develop a range of Thin Soft Layered Actuators (tSLAs). The tSLAs are soft pneumatic actuators consisting of planar 2D geometrical designs, fabricated layer by layer via lamination of silicone and used to create thin PneuNets. As demonstrated by our preliminary results, this fabrication technique can be used to create tSLAs in a highly controlled way with several potential applications (i.e. biomedical, search and rescue, manipulation). Although further work is required to develop design and optimization tools for these systems, the prototypes demonstrated here demonstrate the many exciting opportunities for future application of this work.

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REFERENCES

1. Miyashita, S. et al. Ingestible, controllable, and degradable origami robot for patching stomach wounds. In: *2016 IEEE International Conference on Robotics and Automation (ICRA), 16-21 May 2016*, 2016, pp.909-916.
2. Russo, S. et al. Soft pop-up mechanisms for micro surgical tools: Design and characterization of compliant millimeter-scale articulated structures. In: *2016 IEEE International Conference on Robotics and Automation (ICRA), 16-21 May 2016*, 2016, pp.750-757.
3. Sun, Y. et al. A miniature soft robotic manipulator based on novel fabrication methods. *IEEE Robotics and Automation Letters.* 2016, **1**(2), pp.617-623.
4. Wu, W. et al. Omnidirectional Printing of 3D Microvascular Networks. *Advanced Materials.* 2011, **23**(24), pp.H178-H183.
5. Muth, J.T. et al. Embedded 3D Printing of Strain Sensors within Highly Stretchable Elastomers. *Advanced Materials.* 2014, **26**(36), pp.6307-6312.
6. Mutlu, R. et al. Effect of flexure hinge type on a 3D printed fully compliant prosthetic finger. In: *IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM*, 2015, pp.790-795.
7. Marchese, A.D. et al. A Recipe for Soft Fluidic Elastomer Robots. *Soft Robotics.* 2015, **2**(1), pp.7-25.
8. Bryan, N.P. et al. 3D printing antagonistic systems of artificial muscle using projection stereolithography. *Bioinspiration & Biomimetics.* 2015, **10**(5), p.055003.
9. Patel, D.K. et al. Highly Stretchable and UV Curable Elastomers for Digital Light Processing Based 3D Printing. *Advanced Materials.* 2017, pp.1606000-n/a.
10. Park, Y.L. et al. Fingertip force control with embedded fiber Bragg grating sensors. In: *2008 IEEE International Conference on Robotics and Automation, 19-23 May 2008*, 2008, pp.3431-3436.
11. Gafford, J. et al. Shape Deposition Manufacturing of a Soft, Atraumatic, Deployable Surgical Grasper1. *Journal of Medical Devices.* 2014, **8**(3), pp.030927-030927-3.
12. Shepherd, R.F. et al. Multigait soft robot. *Proceedings of the National Academy of Sciences.* 2011, **108**(51), pp.20400-20403.
13. Martinez, R.V. et al. Robotic Tentacles with Three-Dimensional Mobility Based on Flexible Elastomers. *Advanced Materials.* 2013, **25**(2), pp.205-212.
14. Chossat, J.B. et al. A Soft Strain Sensor Based on Ionic and Metal Liquids. *IEEE Sensors Journal.* 2013, **13**(9), pp.3405-3414.
15. Stokes, A.A. et al. A Hybrid Combining Hard and Soft Robots. *Soft Robotics.* 2013, **1**(1), pp.70-74.
16. Zhao, H. et al. Scalable manufacturing of high force wearable soft actuators. *Extreme Mechanics Letters.* 2015, **3**, pp.89-104.
17. Wehner, M. et al. An integrated design and fabrication strategy for entirely soft, autonomous robots. *Nature.* 2016, **536**(7617), pp.451-455.
18. Martinez, R.V. et al. Elastomeric Origami: Programmable Paper-Elastomer Composites as Pneumatic Actuators. *Advanced Functional Materials.* 2012, **22**(7), pp.1376-1384.
19. Onal, C.D. and Rus, D. A modular approach to soft robots. In: *2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), 24-27 June 2012*, 2012, pp.1038-1045.
20. Ou, J. et al. aeroMorph - Heat-sealing Inflatable Shape-change Materials for Interaction Design. In: *Proceedings of the 29th Annual Symposium on User Interface Software and Technology, Tokyo, Japan*. 2984520: ACM, 2016, pp.121-132.
21. Pikul, J.H. et al. Stretchable surfaces with programmable 3D texture morphing for synthetic camouflaging skins. *Science.* 2017, **358**(6360), pp.210-214.
22. Stanley, A.A. and Okamura, A.M. Deformable Model-Based Methods for Shape Control of a Haptic Jamming Surface. *IEEE Transactions on Visualization and Computer Graphics.* 2017, **23**(2), pp.1029-1041.
23. Mosadegh, B. et al. Pneumatic Networks for Soft Robotics that Actuate Rapidly. *Advanced Functional Materials.* 2014, **24**(15), pp.2163-2170.
24. Park, Y.L. et al. A soft wearable robotic device for active knee motions using flat pneumatic artificial muscles. In: *2014 IEEE International Conference on Robotics and Automation (ICRA), May 31 2014-June 7 2014*, 2014, pp.4805-4810.
25. Khin, P. et al. Soft haptics using soft actuator and soft sensor. In: *Biomedical Robotics and Biomechatronics (BioRob), 2016 6th IEEE International Conference on*: IEEE, 2016, pp.1272-1276.
26. Morimoto, T.K. and Okamura, A.M. Design of 3-D Printed Concentric Tube Robots. *IEEE Transactions on Robotics.* 2016, **32**(6), pp.1419-1430.
27. Yuen, M.C. and Kramer, R.K. Fabricating microchannels in elastomer substrates for stretchable electronics. In: *ASME 2016 11th International Manufacturing Science and Engineering Conference, MSEC 2016*, 2016.
28. Atalay, A. et al. Batch Fabrication of Customizable Silicone-Textile Composite Capacitive Strain Sensors for Human Motion Tracking. *Advanced Materials Technologies.* 2017, **2**(9), pp.1700136-n/a.