4D Printing of Soft Robotic Facial Muscles

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Abstract:

4D printing is an emerging technology that prints 3D structures with smart materials that can respond to external stimuli and change shape over time. 4D printing represents a major manufacturing paradigm shift from single-function static structures to dynamic structures with highly integrated functionalities. Direct printing of dynamic structures can provide great benefits (e.g., design freedom, reduced weight, volume, and cost) to a wide variety of applications, such as sensors and actuators, and robotics. Soft robotics is a new direction of robotics in which hard and rigid components are replaced by soft and flexible materials to mimic actuation mechanisms in life, which are crucial for dealing with uncertain and dynamic tasks or environments. However, little research on direct printing of soft robotics has been reported. This paper presents a study on 4D printing of soft robotic facial muscles. Due to the short history of 4D printing, only a few smart materials have been successfully 4D printed, such as shape memory and thermo-responsive polymers, which have relatively small strains (~8%). In order to produce the large motion needed for facial muscles, dielectric elastomer actuators (DEAs), operating like a capacitor with a sheet of elastomer sandwiched by two compliant electrodes and known as artificial muscle for its high elastic energy density and capability of producing large strains (~200%) compared to other smart materials, is chosen as the actuator for our robotic facial muscles. In this paper, we report the first fully 4D printed soft robotic face using DEAs. A literature review on DEAs is first presented. In order to select the right material for our soft robotic face, the performance of different silicone-based candidate materials is tested and compared. A soft robotic face is then designed and fabricated using the selected material to achieve facial emotions by the motion of its lip and pupils actuated by the DEAs. This study demonstrates a 4D printed soft robotic face for the first time and the potential of 4D printing of soft robotics.

1. Introduction

Robots are typically pictured as machines with rigid bodies and rigid motions. Soft robotics is a new direction of robotics in which hard and rigid components are replaced by soft and compliant materials to mimic actuation mechanisms in life. These soft robots are embedded with various sensors and actuators. One of the most important actuators in soft robotics is dielectric elastomer actuator (DEA), which operates like a capacitor with a sheet of elastomer sandwiched by two compliant electrodes, generating deformation under electric field. DEA is typically used as "artificial muscle" to mimic mammalian muscles due to its large strain and energy density. Natural muscle uses many complex mechanisms involving protein motion and regeneration from neural signal, while artificial muscles change in shape when an external stimulus is applied [1]. Some soft biomimetic robotics associated with artificial muscle are earthworm robots [2, 3], hexapod inspired robots [4, 5], Gecko climbing robot [6], and micro flying insect robot [7].

As soft robotics develops over the past decades, the manufacturing methods are evolving from traditional machining, casting, and forging to more advanced approaches [8]. Although some soft robots were fabricated using traditional manufacturing processes, the demand for more advanced soft robotics has spurred the development of new manufacturing methods, such as shape deposition methods (SDM) and smart composite microstructures (SCM). SDM, a solid freeform fabrication (SFF) process, requires subtractive and additive manufacturing processes [9]. The subtractive manufacturing processes causes high energy consumption and large wastes of materials. SCM integrates the rigid structures with flexure joints and links, which is a fabrication process typically using laser micromachining methods [10]. These advanced manufacturing processes provide freedom in designing new types of 3D structured soft robots. Nonetheless, the manufacturing time and cost are still expensive for these methods. In addition, the complex manufacturing processes limit the complexity of robotic geometry and design freedom. Therefore, in order to further improve the freedom of design, the ease of fabrication and the manufacturing efficiency in time and costs, simpler and more direct manufacturing technologies are desired for making soft robotics.

3D printing technologies have made significant strides during the past decades enabling the direct fabrication of 3D structures. 4D printing, as an extension of 3D printing, is an emerging technology that prints 3D structures with smart materials, which can respond to external stimuli and change shape or properties over time. 4D printing represents a major manufacturing paradigm shift from single-function static structures to dynamic structures with highly integrated functionalities. Direct printing of dynamic structures can provide great benefits (e.g., design freedom, reduced time and cost) for a wide variety of applications, such as sensors, actuators, and robotics. Due to its short history, only a few smart materials have been successfully 4D printed for various applications, including temperature-responsive polymers [11], shape memory polymers [12, 13], and ionic electroactive polymers [14]. And few publications are found on direct printing of dielectric elastomers for making soft robotics. Clearly more research is required in this promising direction due to the simple operation and high energy density of dielectric elastomers. In this paper, we will demonstrate the promise of 4D printing of dielectric elastomers with the first fully printed soft robotic face that can smile upon application of voltage.

This paper is organized as follows. In section 2, a comprehensive literature review is presented on dielectric elastomer actuators. In section 3, the detailed fabrication procedure of dielectric elastomer actuators is discussed, including material selection, fabrication process, and the issues encountered. In section 4, preliminary dielectric tests on simple dielectric elastomer actuators is performed to test their performance, the knowledge of which is then used for designing facial actuators. In section 5, a functional soft facial robot is designed and tested. Conclusions are given in section 6, and future works are discussed in section 7.

2. Literature review

Dielectric elastomer (DE), a group of electroactive polymers (EAP), is a kind of smart material that can generate large strains under electric field. There have been many applications of DEAs since 1990s, such as robotics [15], active vibration control of structures [16], and energy harvesting [17], due to its lightweight and high elastic energy density. Two of the most common DE materials are acrylic and silicone elastomers. Both have their own advantages and disadvantages. Specifically, acrylic elastomers can produce relatively large strain up to 380% and have high dielectric constant, while silicones generally have high electromechanical response speed, long durability, and large range of operating temperature [18]. Most of silicone products are in liquid form or gel form, and can easily be turned into solid form via certain curing processes. Due to the ease of processing and customization, silicone has wider applications than acrylic elastomer, which is typically in solid form.

The properties of dielectric elastomers play a significant role on their applicability for 4D printing applications. Some desirable properties for producing large strain include high dielectric constant, high breakdown strength, and low Young's modulus. Many investigations have been reported on various aspects of DEAs, such as the geometry of electrodes [16], the breakdown strength [19-21], the effect of pre-strain on dielectric elastomers [22-24], and the enhancement of silicone dielectric and mechanical properties[1, 25-30]. One study demonstrates a heart shape of DEA, which could expand and remain in heart shape with fast response at a high frequency of 20 kHz [16].

DEAs typically break down in three different ways, the electrical, the partial discharge, and the thermally initiated breakdown [19]. The partial discharge and thermally initiated breakdowns during the test period can be mitigated [19]. The electrical breakdown, also called dielectric breakdown, limits the maximum voltage that can be applied on DEAs, and thus limits the DEAs strain generation. Dielectric breakdown strength is also dependent on the material physical properties, such as mechanical stiffness, thickness, and pre-strain. The empirical results showed that the dielectric breakdown strength of silicone elastomer films as actuators can be enhanced by decreasing thickness or increasing pre-strain [20]. In addition, un-cured or not fully cured silicone gel has a comparatively lower dielectric breakdown strength than fully cured silicone [21].

The silicone elastomer generally has a maximum uniaxial elongation larger than 75%, and the pre-strain of elastomers have been shown by experiments and simulations as an effective approach to increase their maximum elongation [22]. The maximum strain of a uniaxial actuator made with Sylgard 186 silicone elastomer increased by 10 times from 7.7% to 80% when a 75% pre-strain was applied [24]. However, it was reported that excessive pre-strain could stiffen the elastomer and increase the requirement for actuation voltage. From experiments, Dow Corning HS3 RTV silicone DEA was shown to have a peak of elongation with a pre-strain of about 15%. In addition, from experiments, the softest elastomer is not necessarily the best choice to achieve the largest deformation, because the dielectric constant of the softest elastomer is not the highest [24].

It is desirable to have a large dielectric constant for large electrostatic pressure, which can produce large mechanical strain. Many different approaches have been developed for increasing the dielectric constant of dielectric elastomers. Three approaches were explored, including random composites, field-structured composites, and new synthetic polymers [1]. To illustrate, random composite approach is to fill and disperse either solid (powders) or liquid materials into dielectric elastomer, such as ferro/piezoelectric ceramics, metal conductive particles, and organic polymers. Field-structured composite approach is by mixing dielectric elastomers with some ferro/piezoelectric ceramics and curing them at an external electric field to form the dipolar molecular structure so as to increase dielectric constant. The polymer synthesis approach creates new molecular-structure for dielectric elastomer materials by copolymerization.

For silicone elastomer, random composite is a typical approach for enhancing dielectric constant by studying the impact of the types and content of fillers on the DEAs performance. For example, some high dielectric constant materials were added in pure silicone to enhance its dielectric constant, such as ferro/piezoelectric ceramics (titanium dioxide and $BaTiO3$ powders) [25, 26] and multi-walled carbon nanotubes [27]. However, adding high dielectric constant materials may increase the elastic modulus and the decrease of the breakdown strength, which are not desirable for DEAs [26]. Softening the materials is another type of random composite method through adding plasticizers to enable large deformation at relatively low electric field [28]. In addition, there are examples demonstrating the synthesis approaches to improve silicone dielectric constant, such as copolymerizing copper-catalysed azide-alkyne 1,3-dipolar cycloaddition (CuAAC) [29] and polar cyanopropyl group polymers [30].

Although significant progress has been made on improving the properties of dielectric elastomers, little research has been reported on direct printing of them. One study on 3D printing methods for DEAs was reported in 2008 at the University of California at Berkeley presented the 3D printing method for DEAs fabrication [31]. This study covered DEAs design, dielectric breakdown strength study and the design of printable pre-strain structures. Although their DEAs and printable pre-strain structures were designed for silicone elastomers, the dielectric test of silicone DEAs didn't show any good results on mechanical strain or deformation. In addition, they did not demonstrate any soft robotic applications with their printed DEAs. In 2009, a contributive paper published in Japan presented a new approach to the fabrication of soft dielectric elastomer actuators using a 3D printing process [32]. They emphasized that the advantageous aspect of 3D printing processes is the capability to form complex three-dimensional structures, like actuators and sensors, through relatively direct fabrication methods. A design of the pre-strain of 3D printed DEAs was also demonstrated.

The literature survey reveals that extensive research has been conducted on the properties of DEAs (e.g., dielectric breakdown strength, effects of pre-strain, dielectric constant) while their fabrication methods have been largely overlooked. The very few research on the 3D printed DEAs has been very preliminary, and no soft robotics have been made with 3D printed DEAs. In addition, the design freedom endowed by 3D printing techniques is not well exploited. This paper is to demonstrate the first fully printed soft robotic face made with 3D printed DEAs.

3. Dielectric Elastomer Actuators Fabrication

A typical DEA consists of two components: a dielectric elastomer film and compliant electrodes. For most of dielectric elastomers to produce a large strain, a common strategy is to pre-stretch the dielectric elastomer film to increase its dielectric constant. As a result, a rigid frame is typically required for pre-stretching the dielectric elastomer film. One typical configuration for building a pre-stretched DEA is shown in Figure 1. A dielectric elastomer film is stretched over a rigid circular frame with the electrodes area being masked off. Then conductive material is applied by painting or brushing over the film to make electrodes on both sides of the dielectric elastomer, which is sandwiched by the two electrodes. The novel part of our research is to construct the entire DEA configuration via 3D printing techniques, which provide the design freedom for the actuator's geometry, in order to achieve the desired deformation of facial emotions. The rigid frame is printed on a Fused Deposition Modeling (FDM) printer with ABS and the dielectric film and electrodes are printed on a Fab@Home printer, which is a multi-material 3D printer via dual syringe extrusion. The parts are manually assembled to apply pre-strain on the dielectric elastomer film.

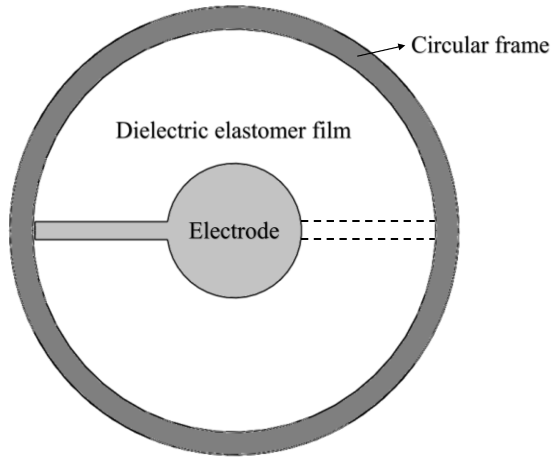


Figure 1. A schematic circular dielectric elastomer actuator

Through applying voltage on the DE actuators, the electrostatic force between the electrodes squeezes the elastomer. The equivalent electromechanical pressure is the Maxwell electrostatic pressure, which is given by:

$$p_{eq} = \varepsilon_0 \varepsilon_r \frac{U^2}{z^2} \tag{1}$$

where ε_0 is the vacuum permittivity, ε_r is the dielectric constant of the elastomer, U is the applied voltage between electrodes and z is the thickness of elastomer membrane [33]. The primary challenge for achieving the apparent DEAs deformation of facial emotions is to select the right dielectric elastomer materials. Certain properties are desired based on the physical principles and our literature survey, such as high dielectric constant and dielectric breakdown strength for generating large pressure, and low Young's modulus for obtaining large strain, as well as low viscosity for the ease of process. Silicone elastomer is chosen for its ease of processing. However, there are hundreds of silicone elastomer products on the market with various properties for different applications. Thus, it is necessary to conduct performance tests to select appropriate silicone elastomers that can generate large strain and operate at relatively low voltage for this facial robot.

a. Dielectric Elastomer Actuator Configurations and Materials

A simple DEA is designed for testing the performance of selected silicone elastomers. The configuration of the test DEA is shown Figure 2, including silicone dielectric elastomer films, carbon conductive grease as electrodes, and circular rigid frames. All components of the DEA are 3D printed. Copper tapes are used as electrical wires to connect the DEA to a voltage source. Four silicone elastomers from different manufacturers are selected based on the aforementioned requirements, including low viscosity, high dielectric constant, high dielectric breakdown strength, and low Young's modulus. These silicone elastomers' specifications are shown in Table 1, and the elongation of materials can represent the capability of stretching. KE-1283, KE-3417 and KE-3494 silicone elastomers are all developed from ShinEtsu Chemical Company in Japan, and Sylgard 170 silicone elastomer is manufactured from Dow Corning Corporation. These silicone elastomer films were printed on Fab@Home printer, which is an extrusion-based multi-material 3D printer.

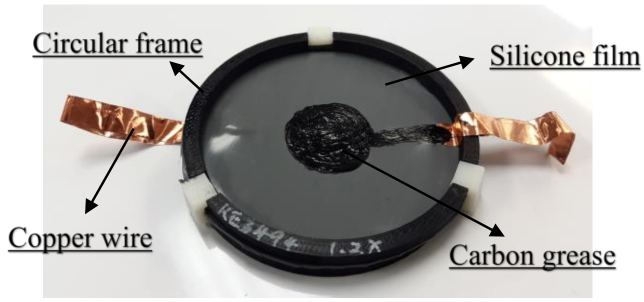


Figure 2. A complete configuration of a circular DEA

Table 1. Specifications of silicone elastomers

	Viscosity (cP)	Elongation (%)	Dielectric Constant	Breakdown Strength (kV/mm)
KE-1283	1950	300	4	25
KE-3417	5000	260	3.2	19.7
KE-3494	5000	250	3.5	25
Sylgard 170	2135	-	2.54	18

These circular rigid frame kits including clamps were printed on Ultimaker 2 with ABS plastic filament. In order to fit in the build area of Fab@Home printer (230x128x100 mm^3), two circular frames with a diameter of 100 mm and height of 6 mm were designed, as shown in Figure 3. The idea of this frame design is to protect the printed electrodes and wire traces on both sides of dielectric elastomer film from touching the stage of the Fab@Home printer during printing process. The DE film is sandwiched between two frames, and three clamps can tightly hold the two frames together.

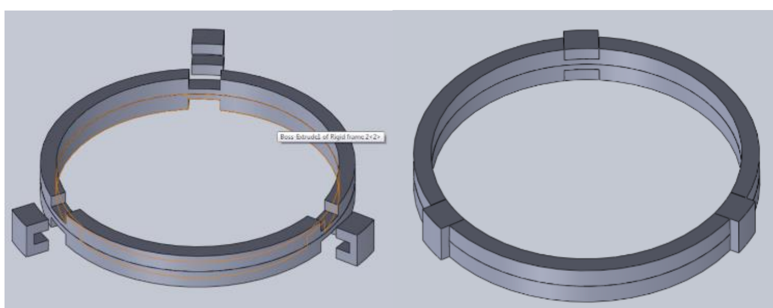


Figure 3. SolidWorks model of assembled frames and clamps.

Carbon conductive grease is used as the electrode materials, and printed on the dielectric elastomer film using the Fab@Home printer. For electrodes, it is critical to select a thin, extremely low-modulus electrode that can provide uniform charge distribution over the surface. MG carbon conductive grease was employed.

b. Fabrication Process

A Fab@Home multi-material printer is used for printing the silicone film and the electrodes. The adjustable process parameters are deposition rate, path speed, path width, path height, and syringe tip nozzle size, as explained in the Table 2. Uniformity and smoothness of printed dielectric elastomer films are dependent on these process parameters. The main procedures in the fabrication process are formulated, including material preparation, printing process, and curing post-process, as described below.

Table 2. The description for processing parameters

Deposition rate	The extruding rate (also extruding pressure)
Path speed	The traveling speed of the print head while printing
Path width	The spacing between two parallel paths
Path height	The single layer thickness
Syringe tip size	Tip nozzle size, also the diameter of extruded material line

a) Material preparation

Before the printing parameters are determined, the materials have to be prepared for printing. One critical issue reported in literature is that air bubbles are easily trapped in viscous materials, inducing the inconsistence in material appearances and properties [26]. An example of a printed silicone film without sufficient degassing shows the bad quality of the print in Figure 4 below. To eliminate the air bubble issue, a vacuum chamber that can extract about 28.5 inches mercury pressure is used to degas the silicone or carbon grease.

The results of the degassing process are influenced by two parameters: extracting pressure and duration. The maximum extracting pressure is determined by the power of pump, while only duration is a controllable parameter. Our experiments show 30 minutes of degassing is sufficient, and it is only effective for materials with viscosity of below 7000 cP, which is good for low and medium viscosity silicones and carbon conductive grease. Through observation, air bubbles in lower viscosity silicones are much easier to remove and come out much faster, such as KE-1283 and Sylgard 170 silicone elastomers. Another issue involved with degassing process is that fast-cure silicone may cure during the degassing process due to the rapid moisture loss in vacuum condition. Of the four selected silicone products, KE-3417 and KE-3494 elastomers cure fast, typically in one hour, while KE-1283 and Sylgard 170 elastomers cure in more than 5 hours. The alternative operation for fast-cure silicone is to degas in three iterations of 10 minutes, instead of one iteration of 30 minutes, and at each break the cured and solidified silicone must be removed so as not to block air bubbles coming out. In order to avoid this issue, the slow-cure silicone elastomers are preferred for easier processing, such as KE-1283 and Sylgard 170 silicones.

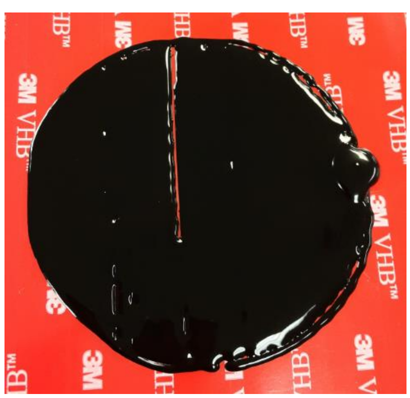


Figure 4. A printed silicone film with insufficient degassing

b) Printing process

The printing process for silicone elastomer was conducted on the Fab@Home printer using a dual-syringe kit with 10 cc syringe barrels and 0.4 mm nozzle size tips, shown in Figure 5. The aforementioned processing parameters, such as deposition rate, path speed, path width, path height, and tip nozzle size, play an important role in determining the uniformity and smoothness of the printed film.

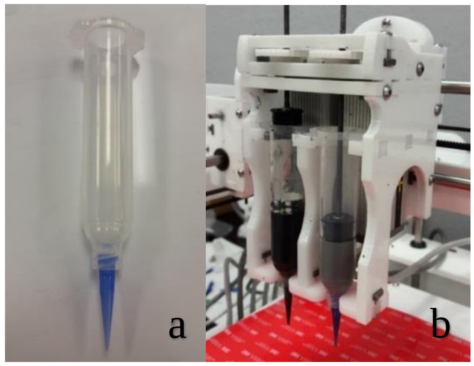


Figure 5. a) A syringe kit of 10 cc barrel and 0.4 mm nozzle tip. b) Dual syringe kit with two different silicone elastomers in barrels

The impact of each parameter on the properties of print is explained below. Path height is associated with the film thickness, which determines how thick each layer will be and how many layers will be built up. For this project, a single layer of elastomer with a various thickness from 100 µm to 500 µm is printed. Single layer can avoid potential air bubble issue between layers, and a thin film is desired to produce large electrostatic pressure according to Equation (1).

Path width and tip nozzle size need to match up in order to print uniform and smooth films without any ridges or valleys, but not necessarily equal. For example, when a 0.4 mm nozzle tip is used, the path width needs to be around 0.4 mm. However, the material viscosity also needs to be taken into account. For low viscosity materials (~2000 cP), such as KE-1283 and Sylgard 170 silicone elastomers, the path width is recommended to be 0.5 mm because they are easy to spread out on the surface. For high viscosity materials (~5000 cP), such as KE-3417 and KE-3494 silicone elastomers, the path width needs to be 0.3 mm based on our experience.

Deposition rate determines how much material is deposited on the substrate per second, while path speed means how fast the dual-syringe print head travels. They are related in some ways. The path speed is held at 30 mm/s, while the deposition rate varies from 0.4 mm^3/s for low viscosity silicones to 1.6 mm^3/s for high viscosity silicones. The reason for that is because higher viscosity silicones require higher extruding pressure, which is typically obtained by specifying a higher deposition rate for the Fab@Home machine.

In addition, the levelness of platform is also a factor influencing the film uniformity, especially for thin films (100 µm). Determining the parameters above is an experimental process to make the appropriate adjustment for different materials. Once the adjustment of parameters above are completed, a uniform and smooth film is obtained, as shown in Figure 6. Because it takes time for pressure to ramp up at the beginning of the print and to wind down at the end of the print, the print quality at the beginning and the end of the printing process is usually not as good. To solve this issue, two extra edges were designed for the silicone as shown in Figure 6.

Figure 6. A good quality silicone elastomer film with extra areas.

c) Post-processing

For curing, different silicone elastomers require totally different processes and conditions, shown in Table 3. The curing conditions may deviate from the conditions listed in Table 3, depending on the environment, such as the temperature and humidity. For example, KE-1283 silicone elastomer films should be cured in 2 hours at 50% relative humidity and 80 °C, but in high humidity circumstance (about 80% relative humidity in our lab), it took almost 4 hours to fully cure them. In addition to curing, pre-strain is necessary to obtain larger strain. Based on literature, higher pre-strain may produce larger strain, but the pre-strain on the silicone dielectric elastomers needs to be much less than the maximum allowed strain for the silicone film to remain soft. In this simple DEAs fabrication, 20% and 30% pre-strains for different silicone elastomers were successfully made, and their maximum allowed strains are more than 200%. The pre-stretched films need to be well aligned for precisely printing symmetric carbon grease electrodes on both sides of films, and then the round corner copper tapes are attached to the electrodes for connecting external voltage source. The round corner copper tapes can prevent the films from concentrated charging that may cause a local dielectric breakdown.

Table 3. Curing conditions for different silicone elastomer

	KE-1283	KE-3417	KE-3494	Sylgard 170
Curing Type	Heat	Moisture	Moisture	Heat
Condition	80 °C	20 °C	20 °C	100 °C
Duration	4 hours	2 hours	6 hours	20 minutes

*Note: Humidity in our lab is about 80% relative humidity (RH).

4. Dielectric Elastomer Performance Tests

The dielectric elastomer performance tests were performed on a custom test setup with a high-voltage DC power supply developed by APEI Company at the University of Arkansas. The power supply was remotely controlled by LabVIEW to step up voltage at 200 V per 250 ms and to collect leakage current at each step. The highest voltage that the power supply can go is about 60 kV. Dielectric breakdown voltages were automatically detected and recorded, and the deformation of DEAs were manually filmed by a camera.

After a silicone elastomer actuator was fabricated, a performance test was performed to measure the breakdown voltages and the maximum strains in order to compare with the performance of DEAs made with other silicones. Figure 7 shows an example of a printed DE film with KE-3494 silicone elastomer, which was pre-stretched by 1.2 times from a 55.8 mm diameter to a 67 mm diameter. Black carbon conductive grease was printed as the electrodes on both sides.

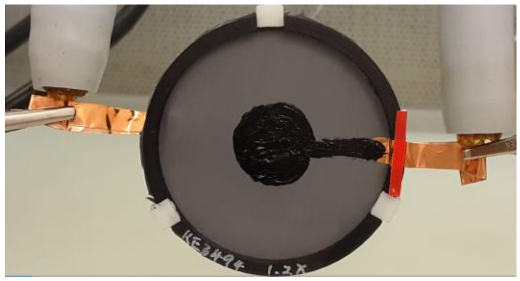
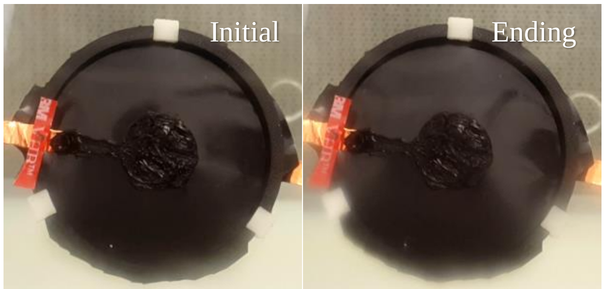


Figure 7. KE-3494 silicone elastomer actuator with 20% pre-strain

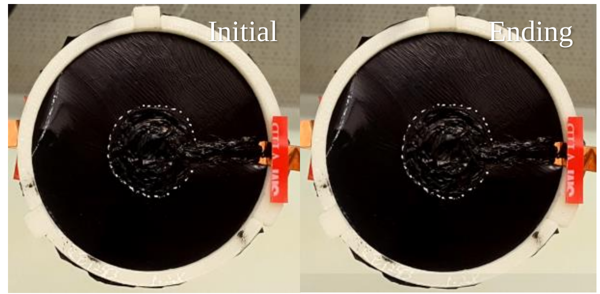
Dielectric breakdown strength measurement is an effective method to test the quality of printed silicone elastomer films and show the effects of pre-strain. Specifically, bad quality of silicone elastomer films caused by air bubbles or other issues commonly weaken their material properties, such as dielectric breakdown strength, dielectric constant, and Young's modulus. In order to test the dielectric breakdown strength, both dielectric breakdown voltage and film thickness were measured. Table 4 shows the average of four thickness measurements for each silicone film by a micrometer and their tested breakdown voltage, as well as the tested and standard breakdown strength. The standard breakdown strength is tested by the suppliers for the silicone elastomers without pre-strain. In order to test the quality of printed film, the tested dielectric breakdown strength of silicone DEA without pre-strain was measured and compared with the standard breakdown strength as shown in the first row of Table 4. The tested dielectric breakdown strength is approximately the same with standard breakdown strength, which shows the DE film made with 3D printing techniques with degassing process has comparable quality to that made with traditional manufacturing processes. In addition, Table 4 indicates that pre-strain can positively increase the breakdown strength for each silicone elastomer. Moreover, higher pre-strain applied on the elastomer can enhance the capability of silicone elastomer to resist higher breakdown voltage. Thus, the performance tests for silicone elastomers verify that these printed films have good quality, and also validate the effect of pre-strain on the enhancement of dielectric breakdown strength of silicone elastomers as reported from literature.

Table 4. Dielectric breakdown strength measurements

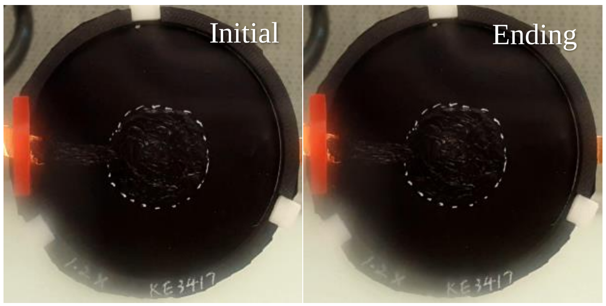
		Thickness (mm)	Tested Breakdown Voltage (kV)	Tested Breakdown Strength (kV/mm)	Standard Breakdown Strength (kV/mm)
No Pre-strain	KE-3417	0.491	9.6	19.6	19.7
Pre-strain 20%	Sylgard 170	0.402	9.6	23.9	18
	KE-1283	0.235	8.2	34.9	25
	KE-3417	0.530	11.2	21.1	19.7
	KE-3494	0.583	17	29.2	25
Pre-strain 30%	KE-3494	0.608	19.6	32.3	25



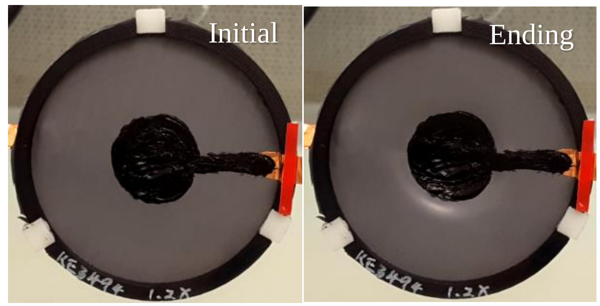
a). 1.2x pre-stretched Sylgard 170 silicone DEAs show 1.4% maximum strain and slightly normal dimension deformation



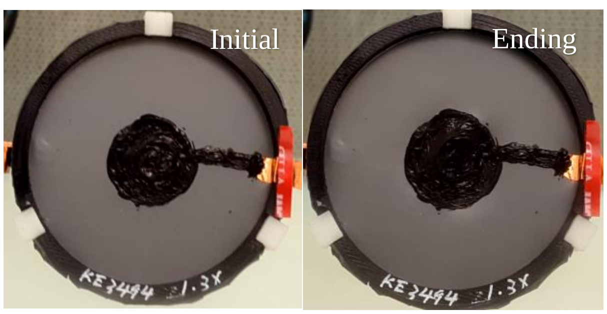
b). 1.2x pre-stretched KE-1283 silicone DEAs show 5.9% maximum strain



c). 1.2x pre-stretched KE-3417 silicone DEAs show about 2.1% maximum strain



d). 1.2x pre-stretched KE-3494 silicone DEAs show about 1.8% strain and obvious normal deformation



s e). 1.3x pre-stretched KE-3494 silicone DEAs show about 2.4% maximum strain and slightly normal deformation

Figure 8. Performance tests for different silicone-based DEAs

Another important performance parameter we hope to obtain through the dielectric tests is the maximum strain for each silicone elastomer, which is crucial for making our facial robots. Figure 8 above shows the initial status and the status before breaking down for each silicone elastomer, as well as its measured maximum strain. All pre-stretched silicone DEA samples have the maximum strain less than 10%, which is similar with previously reported results by the conventional methods in literature. In addition, some of samples, such as Sylgard 170 and KE-3494 silicone elastomers, showed normal (perpendicular to the planar film) deformation, which can be converted into planar deformation when higher pre-strain is applied. A comparison of different pre-strain rate on KE-3494 silicone DEAs indicates that larger pre-strain is helpful to generate more maximum strain and reduce the axial deformation. Among four silicone elastomers, KE-1283 silicone DEA shows the largest maximum strain (5.9%) at 20% pre-strain, and was selected as the dielectric elastomer film for the facial robot.

5. Facial Robotic System

a. The idea of DEA-based facial robotic system

In this paper, a facial robotic system was designed to obtain eye pupils expansion and lip curving activated by DEAs. The initial idea of design is that the expansion of pupils can be directly obtained from circular actuators which can expand isotropically and the smiley lip can be demonstrated from the relative deformation of points at different locations when an electric field is applied, shown in Figure 9. The lip curving is actuated to mimic real muscle. As shown in Figure 9, for circular lip actuators, points a and d locate at the top of the left and right actuators, and points b and c are below the middle actuator. The initial lip is a straight line connecting points a, b, c, and d. As voltage is supplied to system, the lip motion can be demonstrated by the deformation of these four points. Points a and d move upward while points b and c move downward to curve the lip to make a smiley face. In this case, the actuators need to have large strain of at least 10% to demonstrate the facial emotions.

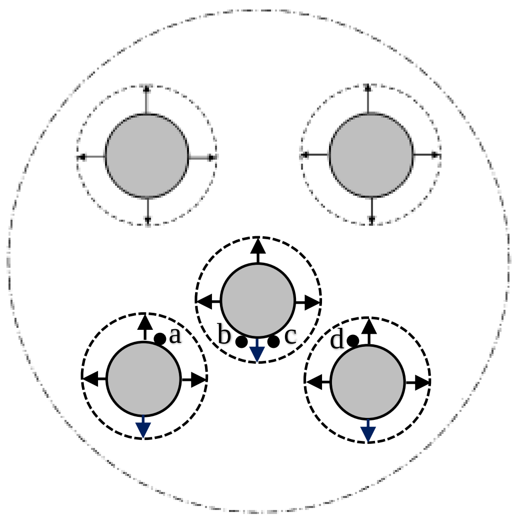
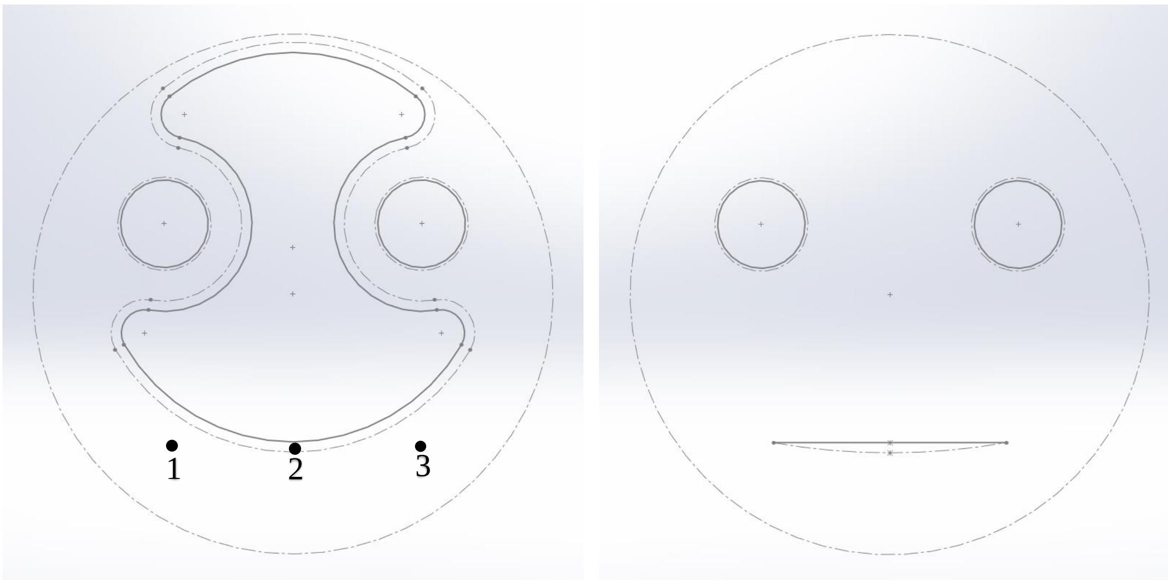


Figure 9. A schematic facial deformation with circular pupil and lip actuators

b. A modified facial robotic system design based on the DEAs performance tests

As shown in Figure 8, the maximum strain of the selected silicone dielectric elastomers are all less than 10% from the preliminary tests using simple DEAs. The largest strain (5.9%) was obtained from the KE-1283 silicone. Thus, facial robotic system is re-designed in attempt to maximize deformation with the relatively small strain of the DEAs. In order to demonstrate the facial emotion, a possible and feasible method is to increase the electrode size several times larger than in previous designs to obtain large deformation. Based on this idea, an alternative design was proposed as shown in Figure 13. To clarify, the expansion of eye pupils are demonstrated by two circular DEAs at top, while the lip deformation is presented by the relative deformation between point 2 at the lowest edge of the large irregular-shaped electrode and two "static" points 1 and 3, shown in Figure 10-a. The deformation of electrodes illustrated by the dash line are calculated using the 5.9% strain of KE-1283 silicone elastomer. As electric field is applied, point 2 follows the bottom deformation of the large electrode moving downward, while points 1 and 3 that are far away from the electrode are expected to have negligible deformation. If the initial lip is designed to be the straight line connecting these three points, shown in Figure 10-b, the relative deformation of point 2 and points 1 and 3 would curve the lip downward to make a smiley face. This design would also take advantage of the capability afforded by 3D printing to make arbitrary shapes.



a). Printed electrodes b). Facial features

Figure 10. A modified design using irregular electrode for small strain actuators

c. Feasibility test of facial robotic system

Besides increasing the electrode size to obtain large deformation, another possible method is increasing the pre-strain rate based on relevant literature and experiments. A 5.9% maximum strain was obtained on the KE-1283 silicone-based DEA with a 20% pre-strain, while the maximum allowed elongation of KE-1283 silicone is 300%. Thus, the capability of KE-1283 silicone under pre-strain condition has not been exploited well. In this facial robotic system, increasing pre-strain from previously 20 % to 50% was attempted to obtain large deformation.

The performance for the facial robotic system was demonstrated via the dielectric test. Dielectric breakdown strength and maximum strain measurements are shown in Table 5. The breakdown strength (35.3 kV/mm) of this 50% pre-stretched KE-1283 silicone elastomer film is slightly higher than the breakdown strength (34.9 kV/mm) of 20% pre-stretched sample in Table 4, and comparatively higher than the standard breakdown strength (18 kV/mm). The operation of the facial robotic system made with this DEA is shown in Figure 11 with the initial status and the final status before dielectric breakdown. However, due to the small strain of about 3.6%, the deformation cannot be clearly visualized. The obtained maximum strain about 3.6% is unexpected, and the potential reasons are only hypothesized. The electrostatic stresses of 20% and 50% pre-stretched KE-1283 silicone films are very close, since their dielectric breakdown strength are close to each other. Thus, it is more likely that small strain on the 50% pre-stretch KE-1283 silicone film is caused by the increased Young's Modulus than that of 20% pre-stretch film. The weakness or defects may be amplified by the higher pre-strain (50%) than the 20% pre-strain, which could lead to worse film qualities (e.g., uniformity, smoothness) and reduce the performance of the DEAs.

Another possibility is that higher pre-strain may make the silicone film stiffer so that cannot produce larger strain, which was reported in literature.

Table 5. Dielectric test results for the facial DEA

	Film Thickness (mm)	Tested Breakdown Voltage (kV)	Tested Breakdown strength (kV/mm)	Standard Breakdown Strength (kV/mm)	Maximum Strain (%)
KE-1283 pre-strain 50%	0.215	7.6	35.3	18	3.6

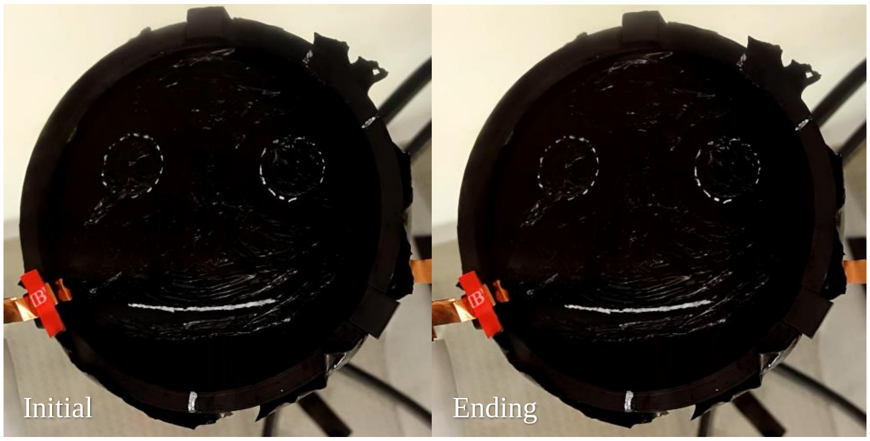


Figure 11. Performance of facial robotic system

6. Conclusions

We reported a fully 4D printed soft robotic face using DEAs in this paper for the first time. First, we provided a comprehensive literature survey on DEAs. Then we formulated a procedure for fabricating DEA using 3D printing techniques. It was shown that the 3D printed dielectric elastomer film has comparable quality to that made with traditional manufacturing processes. In order to select the right material for our soft robotic face, we tested the performance of the DEAs made with different commercial silicone elastomers. KE-1283 was shown to have the best performance among the tested materials. A soft robotic face was then designed and printed with DEAs to actuate the pupils and the lip for obtaining a smiley face. Upon application of voltage, a smiley face was successfully achieved. In conclusion, this paper demonstrated a fully printed soft robotic face and the feasibility of using 3D printing for making DEAs with complex geometry and soft robotics.

7. Future Work

4D printing is a burgeoning field. Base on this research, there is still a huge room to learn and improve the current design. Models need to be developed for understanding and predicting the performance of DEAs to assist the design of the DEAs and soft robots. Further investigations are also needed to optimize process parameters and the geometry of actuators to improve the performance of DEAs and enable more sophisticated soft robotic applications.

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