SUPPLEMENTARY MATERIALS

I. Calculation for Optimum Fabrication of Hydrogel Recipe

Based on Chen’s recipe (22), it was determined that the concentrations of the ingredients should be as follows for the optimum recipe: (i) agarose concentration of 25 mg/mL, (ii) acrylamide concentration of 3.2 mol/L, (iii) MBA concentration of 0.03 mol% of acrylamide, and (iv) UV initiator concentration at 1 mol% of acrylamide. The calculations according to our recipe in Table S1 are as follows:

Table S1: Composition of starting materials for optimum recipe

<table>
<thead>
<tr>
<th>Ingredient/Variable</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylamide</td>
<td>2.85 ml</td>
</tr>
<tr>
<td>Agarose</td>
<td>126.74 mg</td>
</tr>
<tr>
<td>DI Water</td>
<td>2.00 ml</td>
</tr>
<tr>
<td>Photoinitiator</td>
<td>35.99 mg</td>
</tr>
<tr>
<td>MBA (5mg/ml)</td>
<td>0.15 ml</td>
</tr>
<tr>
<td>UV Exposure</td>
<td>120.00 min</td>
</tr>
<tr>
<td>Resting Time</td>
<td>3-7 days</td>
</tr>
</tbody>
</table>

II. Experimental Procedure for Fabrication of Soft Robot

Soft pneumatic actuators (SPA) have been diversified for a variety of application. A dual-system soft robotic endoscope was designed with the aim of multiple degrees of pneumatic action. This section will explore the design and fabrication procedure of this soft robot.

To build SPA with small feature size or even intricate structure, the internal space of the corresponding mold can be inconveniently small or complicated, rendering the existing method – pouring the liquid material into the mold from the top opening – non-effective even with low-viscous liquid. Inverse-flow process has been used here for slight vacuum to absorb the liquid hydrogel mixture from the bottom and slowly fill the whole mold.

Design

The soft robotic endoscope comprises of two components: (I) the endoscope and (II) the actuator.
The endoscope consists of two parts – the main section and the distal section, each with three hollow tubes to control overall movement pneumatically, as shown in Fig. S1. The internal cross-section of each endoscope has one central circular cavity, to house the wiring of the miniature camera, shown in Fig. S1(C). There are three rectangular cavities dispersed radially, 120° from one another. The cavities are rectangular so as to maximize the pressure inflicted on the chamber when air is pumped in by minimizing the total cross sectional area (Pressure=Force/Area). The main section and the distal section of the endoscope component have an overall diameter of 9mm and 5mm respectively. The main section allows better and precise control over the actuation pressure and movement and the distal section allows better maneuvering in smaller lumen.

![Fig. S1. Design for Fabrication of Soft Robot. (A) Overall endoscopic component. (B) Zoomed transparent main endoscopic component. (C) Individual cross-section. (D) Combined cross-section.](image)

The actuator consists of 6 syringe pumps that are linearly actuated using 6 stepper motors, to control the air pressure and air pressure rate being supplied into the endoscopic component of the robot. Three of these 6 motorized pumps are connected to the main component and distal component of the endoscope, allowing 3 independent degrees of freedom (DoF) in each of the two parts of the endoscope. This allows for greater flexibility of the overall device. Arduino MEGA and LabView are used to control the stepper motors, which allows control over the air pump rate and air pressure applied to the endoscope. One pressure sensor is attached to each syringe for monitoring and safety. The entire actuation system is housed in a clear plastic box for safety and ease of transport (Fig. S2).
Fig.S2. Soft Endoscope Robot Actuation. (A) Top view of syringe pump actuator. (B) Side view of syringe pump actuator. (C) Motorized control. (D) Pressure sensor panel.

Unique Features

1. Dual control endoscopic body with varying diameters: Larger diameter component increases stability of the device and smaller diameter component allows easy maneuverability in small lumen.
2. Different sets of linear syringe actuators for each endoscopic part: allows each endoscopic component to move independently of the other, effectively increasing the flexibility of the device along torturous paths.
3. Small, handheld device: portable and easy to store.
4. Pneumatically actuated: Easy external, manual control by varying air pressure and rate. Does not depend on intrinsic material response to external stimuli, allowing better and more accurate control of the movement of the endoscope.
5. Fabricated with customizable hydrogel: Easy preparation, inexpensive, biocompatible, and flexible with desirable mechanical properties.

Fabrication Method

The soft endoscopic robot is fabricated by pouring hydrogel mixture (refer to best recipe preparation method) into 3 dimensionally printed customized molds. One 1mm cylindrical rod and 3 rectangular shafts are accurately secured inside a 9mm cylindrical tube. Hydrogel mixture is sucked up into the tube (to prevent air bubbles) and left to cure under UV light for 2 hours. The
The fabrication process of the bending actuator is as follows:

**Fabrication of Dumb-bell Double Network Hydrogel**

**Step 1: Preparation of Anti-Mold**

1. Print out SOLIDWORKS .stl “Mold Base” and “Mold Grip” using a 3D Printer. Material of choice is VeroClear for the base and ABS Plastic for the grip.

2. Place Mold Grip on top of Mold Base and ensure that they are aligned.

3. Seal the edges and gaps using Smooth-On Sil-Proxy silicone adhesive.
4. Ensure there are no gaps to prevent overflowing of PDMS liquid mixture and leave to dry completely.

Step 2: Preparation of PDMS Mixture

1. Use SYLGARD Silicone Elastomer Part A and B for fabrication of mold.


3. Mix thoroughly using an electronic mixer at 2000 revolutions per minute and 400 rotations per minute for 3 minutes

4. Place the cup into a de-gasser to remove all air bubbles in the mixture for 10 minutes.
5. Carefully pour silicone elastomer mixture over anti-mold. Place in oven at 80 degrees Celsius for 10-15 minutes.

6. After complete curing, de-mold the PDMS mold from the plastic anti-mold. Final hydrogel mold shown on right.

Step 3: Preparation of Hydrogel Mixture and Dumb-bell Shaped Hydrogel

1. Weigh amounts of MBA and Agarose according to Table S1 using an electronic balance.

2. Transfer MBA and Agarose into a flat-bottomed plastic test-tube with cover.

3. DragonLAB micropipette 100-1000 uL was used for measuring volume of acrylamide, MBA and deionized water.

4. Carefully pipette volumes of acrylamide, MBA and deionized water according to Table S1.

5. Mix thoroughly using an electronic mixer at 2000 revolutions per minute and 400 rotations per minute for 3 minutes.

6. Cap tightly and place into a 90 degrees Celsius oven for 10 to 15 minutes. Note: hydrogel mixture is cloudy.

7. When removing hydrogel mixture from the over, ensure the mixture is transparent. This ensures complete melting of Agarose.
8. Using a plastic disposable pipette, transfer hydrogel mixture into PDMS mold.

![Image of PDMS mold](image1)

9. Ensure there are no bubbles by removing bubbles using a sharp needle.

10. Prepare PDMS mold cover using Step 1 and place cover on top of mold containing hydrogel mixture. Allow resting for ten minutes.

![Image of PDMS mold covered](image2)

11. Print “Cover Gripper” using SOLIDWORKS and attach to motor and Arduino. This makes the flipping mechanism. Place covered hydrogel mold in the cover gripper.

![Image of gripper with covered mold](image3)
12. Cover entire set-up with a black box and place under UV exposure for 2 hours.

13. Remove cured hydrogel.

Step 4: Fabrication of Hydrogel Soft Endoscope
1. Cut 3 pieces of 3mm width metal pins at 8 cm length. Cut one piece of 1.5 mm diameter metal pin at 12 cm length.

2. 3D-Print base of hydrogel mold and insert the round metal pin in the center and three flat metal pins around in the slots provided.

3. 3D-Print overall cover for hydrogel mold and place over the pins carefully. Ensure that the round pin is in the center.
4. Cover the top with 3D printed cover piece. Ensure central metal pin fits into the central slot in the cover.

5. Fill a small-width test-tube with the hydrogel mixture. Ensure that the hydrogel mixture is still warm and in liquid form.
6. Slowly immerse covered hydrogel mold into the test-tube. Wait for the bubbles to reach the surface and pop. Use suction to draw hydrogel mixture into the mold.

7. Allow the mixture to rest at room temperature until the hydrogel mixture becomes a gel-like consistency (approx. 10-15 mins). Do not remove when the hydrogel is still in liquid form.
8. Place in a black box and expose to UV light for 2 hours. Ensure that the mold is constantly turned or flipped to allow even exposure of UV throughout the hydrogel.

9. After 2 hours, remove the mold from the UV black box and allow cooling at room temperature.
10. Demold the hydrogel from the mold and thread the outer surface of the hydrogel to restrict radial expansion.

11. Attach 3 PVC tubes to each of the three air cavities on one end of the endoscope using SilProxy adhesive. Completely block the other end using SilProxy.
12. Attach 3 long PVC tubes to connect to air syringes/compressor for actuation.