Shape Design of Gel Robots made of Electroactive Polymer Gel

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ABSTRACT

We propose a novel method to design the shape of small elastic robots made entirely of electroactive polymer (EAP) gel. The gel operates as actuators in microsystems and can facilitate bending motions. In this paper, we bring out directional deformation from originally bending type polymer driven by electric fields. The key idea is to partially reduce the structural flexibility through shape design. To achieve directional motion, we designed gels with wave-shaped surfaces. The thick parts and thin parts of the surface are distributed in either one or two directions. We developed a mollusk type gel robot which shows bi-directional motion. In this way, we propose the method to design the desired deformation response by shape design of the material in advance. This technique is especially suited for MEMS consisting of soft materials.

Keywords: electroactive polymer, shape, design, ionic gel, gel robot, elastic robot, topology

1. INTRODUCTION

Elastic materials have more robustness than stiff materials for collision, especially when they are consisting of micro robots. This is one of the reasons why electroactive polymers are popular for actuators of micro robots[1] and micro manipulators.[2] Although these polymers are elastic, present micro robots are not elastic as a whole like most living animals. Elastic micro robots in the future will likely navigate in rough and narrow space by deforming their own bodies (like amoebas). Recently, a micro robot was presented with conducting polymer hinges which shows bending motions.[1] Although its size is micro-scale, the structure of the robot is the same as macro-scale articulated robots with rotational joints. The motion capability of traditional macro-scale robots has been achieved by adding as many joints as possible to stiff structures.[3,4] It is difficult to take the same approach for micro elastic robots because of their limited space and manifacturing process.

We recently proposed a new design method for elastic robots.[5] We take advantage of their limitation by developing robots consisting entirely of both elastic and self-deformable materials, electroactive polymer gels. We call the robots, "gel robots".[6] We have been developing prototypes of gels robots i.e. starfish-shaped, butterfly-shaped, lizard-shaped and so on. One of the difficulties with gel robots is their limited controllability because of their conceptually infinite degrees of freedom. Our strategy is to reduce the degrees of freedom from infinite to finite. Mechanics theory suggests that the deformation response of elastic materials are sensitive to their own shapes. We designed thin parts to work as actuators, and thick parts to work as structures with the same material.

However, we have not yet developed gel robots whose thick parts and thin parts are distributed. We made thick parts and thin parts respectively, assembled both parts by connecting them together afterwards. The purpose of our study is to find methods to improve controllability of gel robots by reducing structural flexibility. We materialize the gels with wave shaped surfaces. We will discuss the effect of thickness distributed shapes on gel robots' deformation responses.

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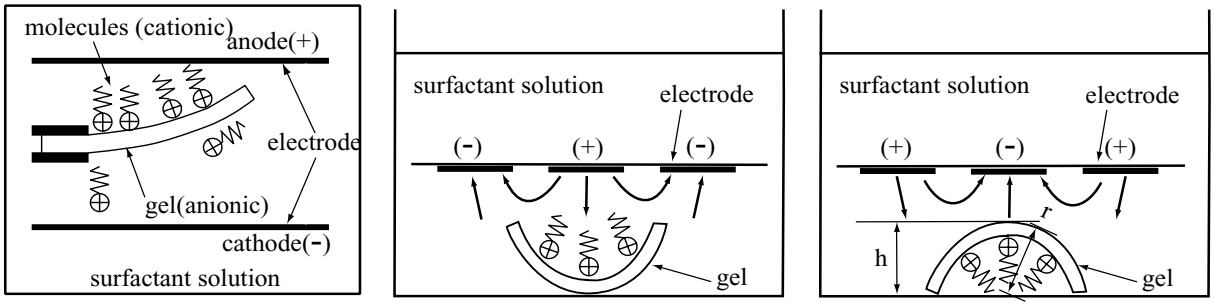


Figure 1. Mechanism of Deformation in Uniform or Spatially Varying Electric Field

2. SHAPE DESIGN OF THE GEL BASED ON MECHANISM

2.1. Modeling of PAMPS Gel Deformation

We selected a typical electro-active polymer gel, poly (2-acrylamido-2-methylpropane sulphonic acid) gel (PAMPS gel)[7,8] and its co-polymer gel from among the variety of electro-active polymers because its ability to undergo large transformations. The gel is driven by an electric field which was generated by parallel electrodes in a surfactant dodecyl-pyridinium chloride(C_{10}PyCl) solution containing sodium sulfate. The gel shows significant bending toward the anode. If the polarity of the electric field is altered repeatedly, the gel bending direction oscillates.

In general, electro-active polymer systems consist of polymer and electrodes either separate or composite. Both types can be modeled by considering the electrical and chemical interactions of a polymer, and an electrochemical field including the solution and the electric field.[9] In this uniform framework (polymers and electrochemical fields), we describe the mechanism of deformation. The deformation of the gel is a result of surface shrinking. Surface shrinking is caused by the binding of the surfactant molecules with the polymer network on the surface of the gel. The binding reaction is an electrical and chemical reaction that characterize the system. From chemical theory, the binding reaction involves two processes: adsorption and propagation. Surfactant molecules which are charged cations are bound to the surface of the gel because the gel network is anionic. This is the adsorption process. The bound molecules subsequently cause anisotropic contraction, which bends the gel towards the anode (the propagation process). We modeled these two processes by considering the gel as an articulated linkage made of polymer chains in two dimensional space.[6] The parameters which describe the jth link are: position vector $\boldsymbol{r}[j]$, orientation vector $\boldsymbol{v}[j]$, thickness $h[j]$, adsorption state parameter $\boldsymbol{ads}[j]$. The adsorption state parameter indicates whether the link has been adsorbed by molecules or not. The state of the gel is expressed as:

$$\boldsymbol{gel} = [\boldsymbol{r}, \boldsymbol{v}, \boldsymbol{h}, \boldsymbol{ads}]. \tag{1}$$

When voltages are applied to the electrodes, the electric field drives the surfactant molecules. The densities of the molecules, which is nearly equal to the electric current densities, affects the probability of binding to the gel surface. When the current density increases, the probability of binding rises. Thus the adsorption process can generally be expressed as:

$$\boldsymbol{ads}[j] = f(\boldsymbol{v}[j], \boldsymbol{i}(\boldsymbol{r}[j])) + g(\boldsymbol{ads}[j]), \tag{2}$$

where $\boldsymbol{i}(\boldsymbol{r}[j])$ is the current density at $\boldsymbol{r}[j]$. The next step is the propagation process. The adsorption state affects the angle of each joint and is expressed generally as:

$$\boldsymbol{dv}[j-1, j] = h(\boldsymbol{ads}[j-m], \cdots, \boldsymbol{ads}[j+m-1]), \tag{3}$$

$$\boldsymbol{v}[j] = \boldsymbol{v}[j-1] + \boldsymbol{dv}[j-1, j]. \tag{4}$$

Adsorbed molecules aggregate together as the joint angles change. Equation (3) is expressed by Equation (5) by assuming that the adsorbed molecules interact only with the molecules on the next link and the thickness of the beam is uniform. The parameter, p_{dv}, calculates the joint angle from the adsorption state and the thickness of the gel.

$$\boldsymbol{dv}[j-1, j] = \frac{2p_{dv}}{h[j-1] + h[j]}(\boldsymbol{ads}[j-1] + \boldsymbol{ads}[j]) \tag{5}$$

Using Equation (5) the orientation and position of each link is calculated. Now we can obtain the parameters of the gel of Equation (2), if we calculate the current density $\boldsymbol{i}(\boldsymbol{r}[\mathrm{j}])$ around each link. Here we summarize the main parameters of this electroactive polymer system; the electrochemical field: current density; the gel: orientation vector; electric or chemical reaction: adsorption. With these equations, we can reduce the complexity of the calculation. Even if either the electric field or the thickness of the gel is not uniform, we can approximate the deformation of the gel by calculating each parameter respectively and substituting to these equations.

We previously found that electric field generated by multiple electrodes in a same plane can drive the free-ended gels[9,10] (see Figure 1). We describe the mechanism of the deformation response, because we use the same configuration in this paper. At first we put strip of the gel on the bottom of the water tank. Then we place multiple electrodes in the same plane above the gel. If we apply different sets of voltages to each electrode, the gel bends towards the anode electrodes, and away from the cathode electrodes. This is because an anode repels surfactant molecules, which adhere to the surface of the gel on the same side as the electrode. In contrast, the cathode electrode attracts the surfactant molecules away from the gel surface. The adsorption speed is much faster than desadsorption speed, which causes the molecules on the surface to accumulate. Hence the curvature becomes larger.

2.2. Shape Design of Gels with Wave-Shaped Surfaces

Deformation of the gel is caused by surface stress which is generated by adsorbed molecules. This means that the proportion of surface area by volume effects the overall deformation of the gel. In a uniform electric field, deformation speed of thin beam gel is supposed to be faster than that of thick one. This assumption is examined experimentally[5] and this can be deduced from Equation (5). Because of the small Young's modulus, a small difference in thickness causes a large difference in deformation response. We found that we can design gel robots so that thin parts work as actuators and thick parts work as structures. From this fact, we can predict:

Conjecture 1 By distributing thick parts and thin parts in the same structure, we will partially reduce the structural flexibility from infinite to finite and at the same time increase the controllability of the gel.

Conjecture 2 If we make the gel with wave-shaped surface, it will deform along the ditch.

Conjecture 3 The difference of the direction of the ditch on either side of the gels will cause bi-directional deformation.

To confirm these hypotheses, we compare simulation and experimental results of deformation response among the gel with smooth surface, the one with wave-shaped surface on only one side, or both sides.

3. PREPARATION OF WAVE SHAPED GEL

3.1. Manufacturing the Wave Shaped Gels as Desired Shapes

The gel we use in this paper is made by radical polymerization.[7] Polymerization of the gel is carried out in a hot water of 323[K] for 24 hours. To obtain the desired shaped gel, we put the monomer solution into the mold in desired shape and polymerize. We describe the manufacturing method we developed, focusing on how to make mold in desired shape, which is a key process. The procedure is divided into five steps, first three steps are data generation and conversions, the forth step is milling the mold and the last one is polymerization. Please remind that the cross sections of the surface data are also used for simulations.

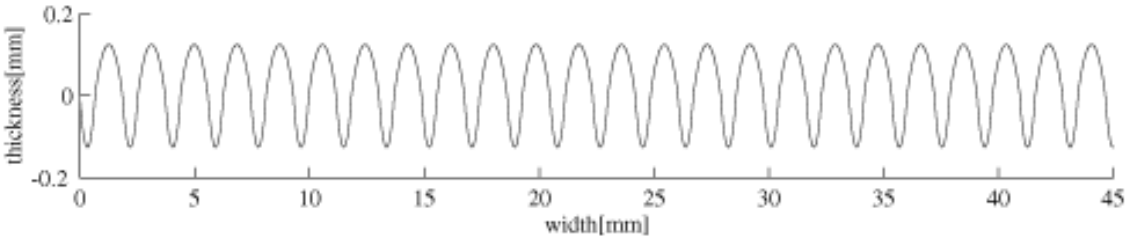
Step 1 Initially, generate numerical surface data of cross section. Here the data is an array of numbers.

Step 2 By extruding the cross-section data in one direction, we obtain three dimensional surface data. We define the data in VRML format.

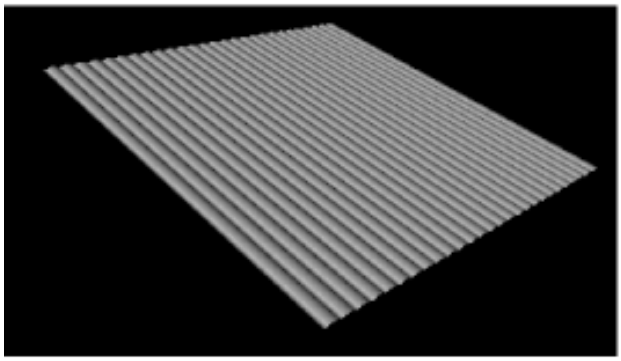
Step 3 Add the frames and marks to 3D surface data. To be used to milling the mold in the next step, save data in DXF format.

Step 4 Cut the mold with NC machine.

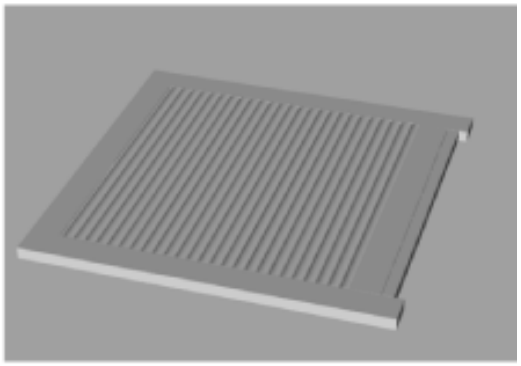
Step 5 Put the monomers into the mold and polymerize in a hot water.



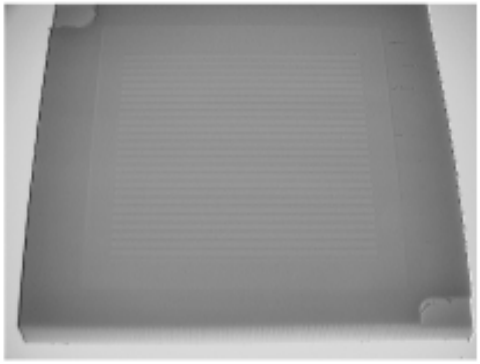
[Step 1] Cross Section Data



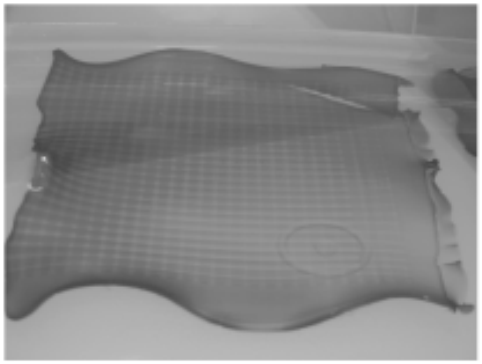
[Step 2] 3D Surface Data



[Step 3] 3D Mold Data



[Step 4] Mold cut by Ball Endmil



[Step 5] Gel with Wave Shaped Surface

Figure 2. Manufacturing of the Gel with Wave-Shaped Surface

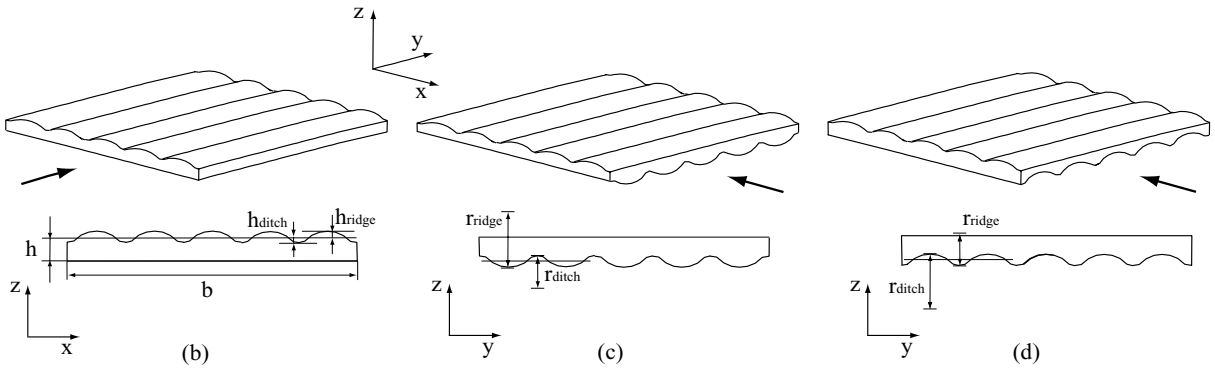


Figure 3. Shapes and Size of the Gel for Experiment

In this case, we make mold by cutting, using NC machining tool. Radius of the ditch need to be larger than the radius of the milling cutter, 0.5[mm]. To meet the above requirement, we cut the edge of circle whose radius is larger than 0.5[mm] and connected on the line. We need to make the mold smaller than the desired size, because polymer gels swell in the solution. The gel becomes 1.4 times larger than the mold size. Appearance of data and mold of each steps are shown in Figure 2.

3.2. Shapes and Sizes of the Gel for Experiment

With manufacturing method we proposed, we prepare four different shapes of the gel. Surfaces of the face side and the reverse side are different. We make gels with mold larger than the specimens. After polymerization, we cut them into pieces, which are to be used in the simulations and experiments. We illustrate the shapes of each gel in Figure 3. The top pictures are of the 3D schematic models of the gel(b), (c) and (d), while the bottom pictures are cross sections when we observe from the direction of each arrow. Their surfaces are the same, although the reverse surfaces change respectively.

(a) Both sides have a planar surface. The thickness of the gel is uniform h= 0.8[mm].

(b) One side has a planar surface and the other side has a wave shaped surface. The average thickness is the same as (a), 0.8[mm] and the distance between the ditch and the average plane h_{ditch} is 0.2[mm].The distance between the ridge and the average plane h_{ridge} is also 0.2 [mm]. Radius of cross section of the ditch r_{ditch} is 0.8[mm], and that of ridge r_{ridge} is 2.1[mm].

(c) Both sides have a wave shaped surface. The ditch of the face side and the reverse side runs orthogonal to each other. The average thickness h is also the same as (a) and (b), 0.8[mm] and the distance between the ridge and the average plane h_{ridge}, the ditch and the average plane h_{ditch} are 0.2[mm] respectively. A set of radius of cross section of the ditch and ridge are common to the surface and reverse side.

(d) Both sides have a wave shaped surface. Its surface is the same as gel(c). The reverse side is different. Radius of cross section of the ditch r_{ditch}= 2.1[mm], and that of ridge r_{ridge}= 0.8[mm].

Above three specimen are 13[mm] square (size of one side $b = 13[mm]$) and the numbers of ditch is four and the numbers of ridge is five. For comparison, we cut beams with wave shaped surfaces from one of these square shaped specimen. Width of each beam is the same as the width of the ridge. From the same mold of gel (b), we cut beam (b1) vertical to the ditches whose length is 15[mm]. We use square shaped gel with different surfaces for experiment and beam shaped gel for experiments and two dimensional simulations.

4. EXPERIMENTAL SYSTEM

4.1. Simulator and Generator of the Electrochemical Field

Experimental system is consisting of two parts, simulator and generator of the electrochemical field. Input signal is common to simulator and generator, applied voltage data towards pairs or multiple electrodes. We implemented two

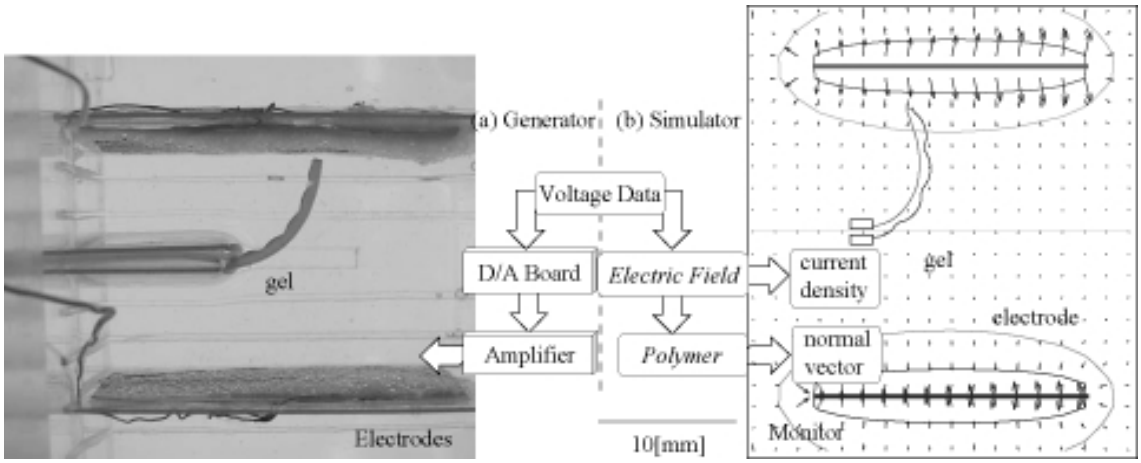


Figure 4. Simulator and Generator of the Electrochemical Field

dimensional simulator for examining deformation response of gels and gel robots based on the previously described model. Whole system works as follows: For initial setup, we select the arrangement of electrodes and the shape and size of the gel for simulation and experiment. To obtain the shape and size data, we cut the cross section of the surface data into desired length. If we set voltage data toward a set of electrodes, the generator converts the electric signals from digital to analog, amplify and generate the electrochemical field using electrodes in the electorate solution. The simulator simultaneously calculates the distribution of the electrochemical field parameter, current density, and approximates the deformation of the gel. Both of them are displayed in real time. The system is shown in Figure 4. The left side shows generator of the real electric field (a) while the right side shows simulator of the system (b). The voltages are controlled by a PC I/O board (RIF-01, Fujitsu Corporation) and amplified by amplifier circuits with a D.C. power supply (PW18-1.8Q, KENWOOD). The transformation of the gel is analyzed by a video microscope (VH7000, Keyence).

To generate a uniform electric field, pairs of parallel electrodes are used and the distance between two electrodes is 30[mm]. To generate a spatially varying electric field to deform gels into concave shapes or convex shapes, multiple electrodes are used. In the latter case, we arranged the electrodes to form a matrix of 3 rows and 3 columns in the same plane. There are a total of eight electrodes. The size of each electrode $d_{ele}$is 10[mm] square. The space between each electrodes $d_{space}$is 5[mm] (Figure 5). The gel is located under the array of electrodes, with the space between the gel and the array l being 10[mm].

4.2. Experimental Procedure

With this system, experiments were performed in three steps. First, we simulated the deformation of beam shaped gel with (b1) wave shaped on the face side and plane surface on the reverse side. We apply uniform electric field to them by pairs of electrodes. The voltage between a pair of electrodes is 10[V]. The length of the time applying the electric field is 20[s]. We examine two cases. In one case, the wave shaped surface faces to the anode side (b1a). And in the other case, the wave shaped surface faces to the cathode side (b1c). We compare the deformation between these two cases. Evaluation standard is the distance between the fixed and free end. This is because the distance between the fixed end and the free end supposed to become smaller if the beam shows large deformation.

Second, based on the basic experiment and simulation, we apply spatially varying electric field generated by a matrix of electrodes to three types of square shaped gels. We place square gels just below the center cathode electrode so as to deform it into a convex shape. We apply -10[V] to the electrode right above the gel and 0[V] to other 8 electrodes. Then we observe the height of the center of the gel from the bottom h (in Figure 1), and at the same time, measure the curvature of the gel $1/r$. We can see what direction are the gels bending along by comparing the curvature at the same height. Each experiments are carried out several times and nearest of the average data are selected because the results are sensitive to the initial shape of the specimen. Finally, we apply -10[V] and 10[V] alternatively right above the (c) and (d) type square shaped gel, and observe the deformations, which is estimated to show bi-directional motions.

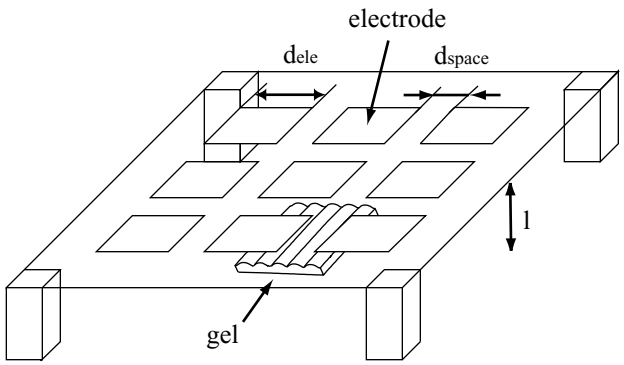


Figure 5. Multiple Electrodes in a Matrix Configuration

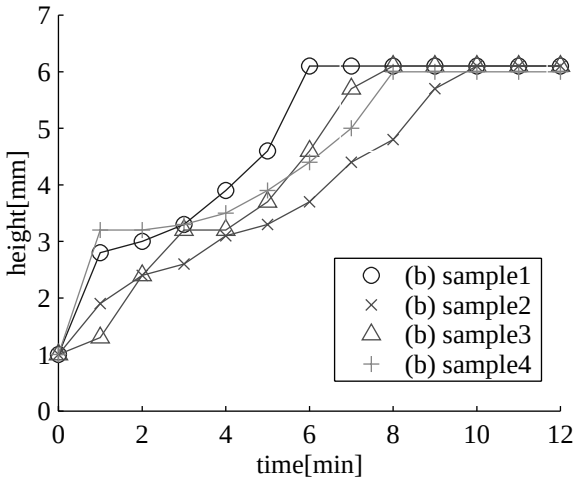


Figure 6. Transition of the Center Height of Gel(b)

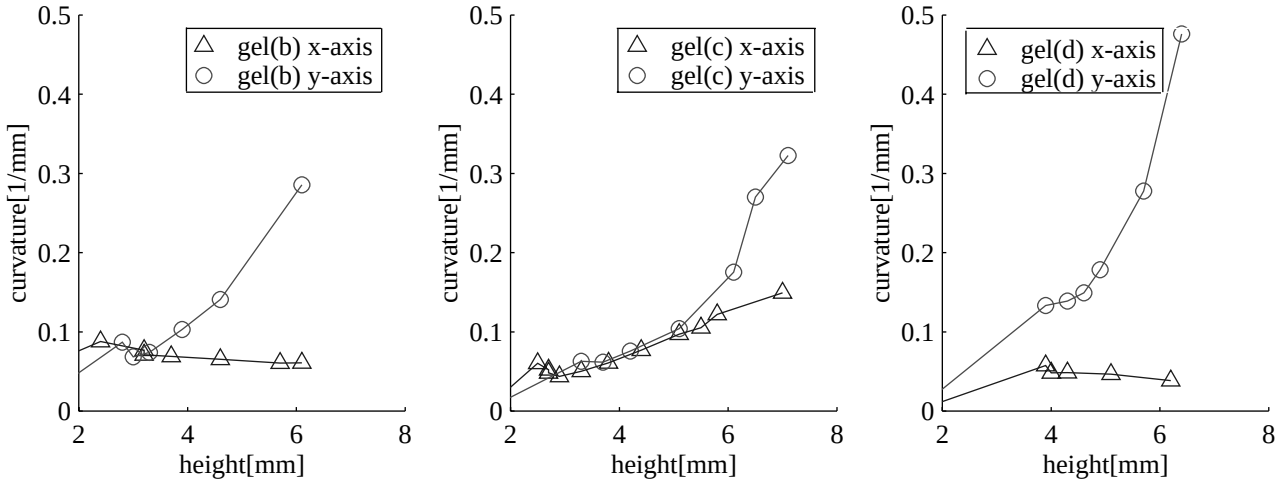


Figure 7. Curvature vs. Center Height of the Gels (b),(c), and (d)

5. UNI- OR BI-DIRECTIONAL DEFORMATION OF THICKNESS DISTRIBUTED GEL AND GEL ROBOTS

5.1. Beam Shaped Gel with Wave or Smooth Surfaces with Fixed End

At first we examined the beam shaped gels and compared the deformation response with different surfaces. We measured the distance between the root and the tip of the gel after applying the uniform electric field. We define that the distance between the root and tip of the gel of (b1a) as d_{b1a}, that of (b1c) as d_{b1c}. Simulated results were: (d_{b1a},d_{b1c})=(13.4, 13.1). Experimental results were: (d_{b1a},d_{b1c})=(14.2, 13.4). In both cases $d_{b1a} > d_{b1c}$. Difference of the distance were clearly shown in the experimental results. If the curvature is large, the distance is likely to be small. We can say that the gel with wave shaped surface on extending side (b1c) deforms larger than the one with wave shaped surface on shrinking side (b1a). This result implies that square shaped gel with ditches on one side deforms along the ditches. Then, what happens to the square shaped gel with ditches on both side; the surface side goes along y-axis, the reverse side goes along x-axis? We can hypothesize from the result that it will become concave shape along x-axis and convex shape along y-axis. In summery, it will bend along the ditches of extending side.

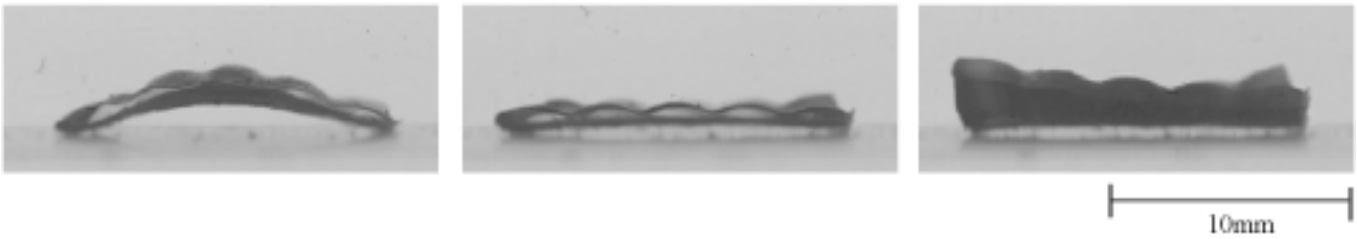


Figure 8. Bi-Directional Deformation of Thickness Distributed Gel (d)

5.2. Square Shaped Gel with Wave or Smooth Surfaces with Free End

To verify the assumption derived from the basic experiment, we applied the electric field to the square shaped gel with various surfaces. Figure 6 illustrates the transition of the (b1) gels' center height. It shows the speed of overall deformation of the gel. Their speeds are uneven because the material property of the gel is also uneven. But the final height is almost the same, almost the half size of their sides. In finite state, they fold up into doubles. These phenomena happen not only on the gel (b) but (a)and (d). According to these results, we decided to compare the curvatures of the surface at the same height. The large curvature implies the large deformation. The graphs are shown in Figure 7. Curvatures are illustrated after the center height becomes more than 2[mm], because the observational error of the curvature is large when the height of the center is small. We will show the results of gel (b), (c), and (d), because the deformation of the gel (a) is unstable and the curvature of the same height cannot be predicted even if we apply the same electric field.

Different from gel(a), gel (b) bends along the ditches. The gel(c) bends along y-axis, the same direction of the ditch on extending surface. The gel(d) also bends along y-axis, but the difference of two curvatures of each direction are larger than that of gel(c). In this way, we checked the idea of shape design improved controllability (Conjecture 1), and the gel with wave shaped surface bend along the ditch(Conjecture 2). From the latter result, we presuppose that if we apply the reverse electric field to the gel (c) and (d), especially the gel (d) will become concave shape along the x-axis. We ascertained that the gel (d) bends as we expected. It showed bi-directional motions (Figure 8)(Conjecture 3). When the polarity of the electrode above the gel is anionic, the gel becomes convex shape along y-axis. When the polarity of the electrode is reversed, cationic, the gel becomes concave shape along x-axis. We could find the inclination in the gel (c), but the difference was smaller than that of gel (b).

5.3. Discussion on Directional Deformation Considering the Moment of Inertia of Area

Preliminary two dimensional simulation and experimental results which compare the deformation of gel (b1a) and (b1c) only support the deformation response of gel (c) bending along the directions of extending surface. We got the results of bi-directional motions experimentally. To describe the mechanism of directional motions we observed, we need to consider the moment of inertia area I of each cross sections. This is because once the square shaped gel bends, the I of the cross section which is vertical to the axis of bending becomes larger. We can estimate by simple calculation of I of the gel (a) with uniform thickness. At first, the cross section is rectangle, width $b = 15$[mm] and thickness $h = 0.8$[mm]. After applying the electric field, the specimen became convex shape. To be simple, we approximate its final shape as an arc whose center angle is π. Then the radius of its curvature r approximately expressed as b/π because the length of the specimen along the side doesn't change. From the formula of the moment of inertia area, the moment of inertia area at initial state I_{init} and the final state I_{final} are:

$$I_{init} = \frac{1}{12}bh^3, \quad I_{final} \simeq 0.3hr^3 = \frac{0.3}{\pi^3}b^3h(\text{if } r \gg h) \tag{6}$$

Comparing I_{init} and I_{final}, I_{final} is far larger than I_{init}, which means the structural stiffness of this cross section increases as the deformation progresses. By substituting the numbers of this gel(a), the increase of I becomes obvious; $I_{init} \simeq 0.55$ and $I_{final} \simeq 17$.

6. CONCLUSION

In this paper, we have focused on the shape of the material that brings out different deformation response, rather than the materials themselves. The idea comes from the fact that the shape defines the structural flexibility. The controllability of flexible objects is improved by shape design which partially reduces flexibility. We have developed a method to model and materialize a thickness distributed gel of milli-order size and found a new way of moving the gels. Our shape design method is applicable to realize micro-scale elastic robots because shape design of small elastic robots will be achieved by one-step molding or casting in micro-scale. Future direction of this research is to make the pitch of the ditches to micro-scale and distribute them in different directions on the same plane. If we can materialize gel with folds along different directions, it will show a different deformation response according to the location when the applied electric field is uniform. The controllability of such a gel will be improved compared with a uniform thickness gel.

We have examined the shape effect on the deformation response using both simulations and experiments. We have shown some example translation of the deformation response by shape design. The controllability of the wave shaped surfaces were improved compared with smooth shaped surfaces. The deformation responses of the uniform thickness gels changed by times, while that of the thickness distributed gels were stable. Uni- or bi- directional motions were achieved by designing the shape of the gels with wave shaped surface along one or two directions. Shape design is effective especially at initial conditions because the deformation of the material is restricted along the directions of its surface. We have new findings from the experimental results that once the deformation starts, the deformed shape effects the deformation response at a moment. It doesn't happen in two dimensional space. We will design three dimensional simulations and clarify the deformation mechanism carefully as well as develop the manufacturing process.

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