Wave-shape pattern control of electroactive polymer gel robots

Mihoko Otake, Yoshihiko Nakamura, Masayuki Inaba and Hirochika Inoue

Department of Mechano-Informatics, Graduate School of Information Science and Technology, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan
E-mail: otake@ynl.t.u-tokyo.ac.jp

Abstract. This paper proposes wave-shape pattern control method for whole-body deformable robots containing electroactive polymers. Mechanisms consisting of a typical electroactive polymer gel containing poly 2 -acrylamido -2- methylpropane sulfonic acid (PAMPS), named 'gel robots', have been designed, developed, and controlled experimentally. We faced a common problem called, the degrees-of-freedom problem, namely controlling many points on the gel surface with a small number of inputs. In order to solve the problem, we once reduced the number of inputs to one, and discovered that wave-shape pattern evolves for the beam-shaped gel even in a constant uniform electric field. This method makes use of the pattern formation. Wave-shaped gels with varying curvature are obtained by switching the polarity of a spatially uniform electric field. The method is verified through experiments which are carefully designed based on numerical simulations.

1 Introduction

Electroactive polymers [1] change their shapes in the electric fields. The fact motivated us to design the whole-body deformable robots. The purpose of this study is to establish methods for deriving a variety of shapes and motions of deformable robots whose bodies are made of active materials. Shape control of such mechanisms is difficult, which is commonly called the degrees-of-freedom problem [2], namely a problem of controlling many points of continuum with a small number of inputs. In order to explore the high dimensional configuration space of elastic objects [3], probabilistic roadmaps was applied.

Osada et al. developed a surfactant-driven ionic polymer gel which is made of poly 2-acrylamido-2-methylpropane sulfonic acid (PAMPS), and well known for its large deformation[4]. Although the gel reversibly bends and stretches by alternating the polarity of the electric fields, the spatiotemporal pattern formation has not been studied in depth. We have been developing deformable machines utilizing the gel, hereafter called "gel robots", and proposed methods for exploiting a variety of shapes and motions of the gel[5–8]. The methods were applied and succeeded in generating variety of motions such as beam-shaped gels curling around an object and starfish-shaped gels turning over[9]. The pattern formation process of the gel was analyzed refering to the living things that also have deformable bodies. They accumulate the temporal sequence of input and build their bodies in the developmental process called morphogenesis. Uniform structures are converted to complex organs in a uniform

gradient field. Learning from morphogenesis, we applied a uniform gradient electric field to a straight beam of gel, which exhibited wave-shape pattern formation[10]. The experimental results suggest that complex shapes can be generated by simple electric fields.

In this paper, a method for generating a variety of wave-shapes is proposed making use of pattern formation theory of electroactive polymer gels. The wave-shape pattern formation experiments are described in the following section. Then, the wave-shape pattern control method is derived and verified through control experiments.

2 Wave-shape pattern formation of electroactive polymer gel

2.1 Experimental methods

The gel was prepared by radical copolymerization at 323K for 48 hours. The total monomer concentration in N, N-dimethylformamide was kept at 3.0M in the presence of 0.01M N,N'- methylenebisacrylamide (MBAA) as a cross-linking agent and 0.01M α, α' - azobis (isobutyronitrile) (AIBN) as an initiator. Monomers were 2 - acrylamido -2- methylpropanesulfonic acid (AMPS), n-stearyl acrylate (SA), and acrylic acid (AA) with the composition (AMPS: SA: AA) = (20: 5: 75). After the polymerizations, the gel was immersed in a large amount of pure water to remove un-reacted reagents until it reached an equilibrium state. The degree of swelling of the gel was 20. This number is determined as a weight ratio of the water-swollen gel to its dry state, which characterizes the gel. In order to apply the electric field, the gel was immersed in a dilute solution of 0.01M lauryl pyridinium chloride containing 0.03M sodium sulphate. All experiments were carried out at a room temperature of 25 °C.

The experimental setup included a pair of parallel platinum plate electrodes of 25 [mm] wide and 40 [mm] long each, which were horizontally placed with 40 [mm] vertical spacing between them. A beam-shaped gel of 4 [mm] wide, 21 [mm] long, and 1[mm] thick was also horizontally placed inbetween with one end fixed for 5 [mm] and the other end free. The vertical section of the experimental setup is seen in Fig. 1. The two electrodes and the gel were immersed in the solution. A uniform electric field was applied by the electrodes. The current density was kept constant by a galvanostat at 0.15 [mA/mm^2] for 600 [s]. The deformation of the gel was monitored and recorded by a video microscope. The fixture size was set small so as not to disturb the electric field. As shown in Fig.1, the x-axis was chosen as the horizontal line going through the fixed end of the gel, while the y-axis was the vertical one also going through the fixed end. The electrodes were placed at y=$\pm$20 [mm]. Let ϕ be an angle between the tangential line of the gel at the free end and the x-axis.

2.2 Experimental results

With the constant electric field, the gel showed waving motion and a wave shape was eventually generated after a while. First the gel bent toward the anode side. When ϕ

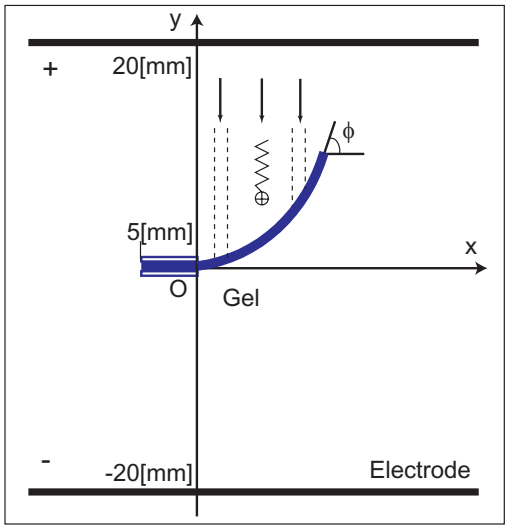

Fig. 1. Deformation process of a surfactant driven ionic polymer gel illustrated with experimental setup.

went over $\pi/2$, a portion of gel near the free end started to bend in the other direction. The deformation of root portion remained same. Again, when ϕ went under $\pi/2$, a smaller portion of the gel near the free end started to bend the first direction. Likewise the free end of the gel showed an oscillation. Fig. 2 shows the angle of the tip of the gel ϕ during motion. In the uniform electric field, the beam-shaped gel bent toward the anode side. The tip of the gel showed unclockwise motion in the x-y plane from the initial point (16, 0) [mm]. Angle ϕ increased from 0 and reached the local maximum of ϕ_1=2.11[rad] at $t_1 = 50$[s]. It didn't stop when the tip became vertical to the electrode and parallel to the electric field. Then the direction of the movement of the tip reversed. The angle decreased to the local minimum of $\phi_2 = 1.02$[rad] at $t_2 = 210$[s]. The direction of motion of the tip again reversed to increase ϕ. The angle of the tip became the local maximum of $\phi_3 = 1.80$[rad] at $t_3 = 420$[s], after that it gradually decreased in the course of experiment. The transitional shapes of the gel are shown in Fig. 3. Fig. 3(a) represents the shape of the gel at t_1 when the direction of the tip reversed for the first time. The second extremum of the gel near the tip appeared after t_1. The second extremum grew until the direction of the tip movement reversed in t_2 whose shape are shown in Fig. 3(b). After that, the third extremum appeared. When the tip of the gel reversed at t_3, the gel had three extrema (Fig. 3(c)). The maximum curvature decreased as the numbers of extrema increased. After the third reversing point of the tip, it became difficult to count the numbers of extrema. This is because the curvature became small and exceeded the maximum accuracy of measurement. The whole shape of the gel became mostly vertical to the electrode. In summary, wave-shape pattern formation of the gel observed. The waving rhythm generation was accompanied it.

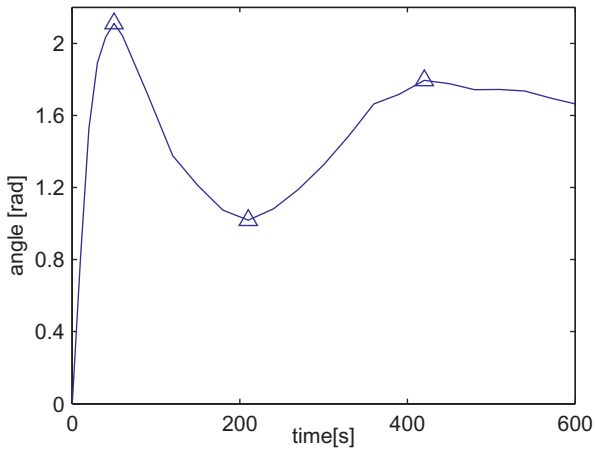

Fig. 2. The angle of the tip of the beam-shaped gel ϕ in a spatio-temporally uniform electric field.

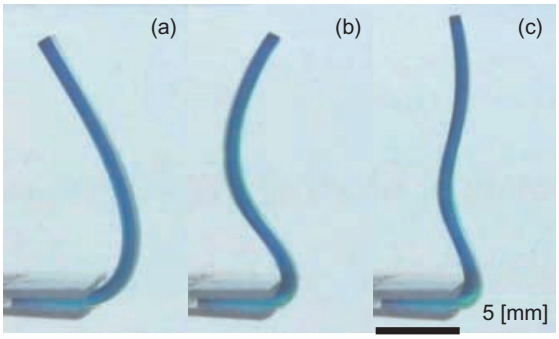

Fig. 3. Deformation of the beam-shaped gel in a spatio-temporally uniform electric field.

2.3 Mechanism of pattern formation

The nonlinearity of the electroactive polymers is the key to understand the mechanism. An ionic polymer gel in an electric field deforms through penetration of the surfactant solution [11]. This process is characterized by the following three steps.

1. Migration of surfactant molecules into the gel driven by the electric field
2. Adsorption of surfactant molecules to the polymers
3. Gel deformation caused by adsorption of surfactant molecules

The state of the gel is characterized by the distribution of adsorbed molecules, which determines its overall shape. Adsorption state transition of the gel is approximated in the following local nonlinear differential equation[10]:

$$\frac{\mathrm{d}\alpha}{\mathrm{dt}} = v_a - v_d = -a\boldsymbol{i}\cdot\boldsymbol{n} - d\alpha. \tag{1}$$

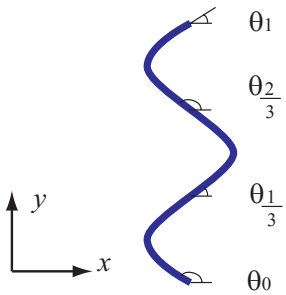

Fig. 4. Definition of the objective shapes with tangential angles in the case of three-half-waved shape

where α is the adsorption rate defined as the molar ratio of bound surfactants to the local sulfonates group of the polymer chains inside the gel; $\boldsymbol{i}$ is the current density vector on the gel surface; $\boldsymbol{n}$ is the normal vector of the gel surface; a and d are association and dissociation constants. The equation shows that the effect of an electric field to a gel is determined by the geometry of the equi-potential surface and the gel surface.

Since the electrodes were placed parallel to the x-axis, the current density vector is written by:

$$\boldsymbol{i} = (i_x, i_y) = i_c(0, -1), \tag{2}$$

with the constant i_c = 0.15[mA/mm^2]. If we take the tangent angle on the gel surface for θ, the normal vector on the surface becomes as follows:

$$\boldsymbol{n} = (n_x, n_y) = (-\sin\theta, \cos\theta). \tag{3}$$

We can obtain the specific expression of equation (1) by substituting equations (2) and (3) into it,

$$\frac{\mathrm{d}\alpha}{\mathrm{dt}} = ai_c\cos\theta - d\alpha. \tag{4}$$

The second term of the right hand side of equation (4) is damping, which originates from the dissociation term in equation (1). If the first term of the right hand side of equation (4) is constant, the answer of the equation is a simple exponential function, which converses to zero. Inclusion of cosine function to the first-order partial differential equation of equation (4) causes rich pattern development. Adsorption reaction causes the mechanical deformation. The deformation determines the subsequent reaction. This interaction of deformation and reaction brings out the wave-shape pattern formation.

3 Wave-shape pattern control of electroactive polymer gel

3.1 Numerical simulation for experiments

Wave-shaped gels with varying curvature were obtained by switching the polarity of a spatially uniform electric field. The period for reversing the polarity was explored through numerical simulation. The polarity of one of the electrodes was either anodic(0) or cathodic(1). A control sequence is described with a time interval and its sequence. A time interval of 10 second was initially selected and its sequence of eight intervals were enumerated from (00000000) to (11111111). Other intervals were also considered every 10 seconds from 20 to 120 seconds. We determined (00001111) with 120 seconds time interval as the best input sequence, which generated three-half-waved shape with large curvature. The performance function was defined with the tangential angle of the gel for determinating input sequence. That of the three-half-waved shape f_3 is described by

$$f_3 = (\theta_{\frac{2}{3}} - \theta_1) + (\theta_{\frac{2}{3}} - \theta_{\frac{1}{3}}) + (\theta_0 - \theta_{\frac{1}{3}}) = \theta_0 - 2\theta_{\frac{1}{3}} + 2\theta_{\frac{2}{3}} - \theta_1, \tag{5}$$

where the suffix of the orientation θ is the normalized length from the root to the arbitrary point. The orientation of the root is θ_0, that of the tip is θ_1, that of the center is $\theta_{\frac{1}{2}}$, that of one third from the root is $\theta_{\frac{1}{3}}$, that of two thirds from the root is $\theta_{\frac{2}{3}}$. Performance function of the shape with x half-waves is noted as f_x. The objective shape with tangential angles is illustrated in Fig. 4. Simulated forms of the gel at every time interval are shown in Fig. 5.

Experiments were conducted. Experimental setup was the same as that of wave-shape pattern formation. The current density was kept constant by a galvanostat at 0.10 [mA/mm^2]. The polarity of the electric field was reversed from anodic(0) to cathodic(1) when the tangential angle at the tip of the gel reached the same values as that of the simulation.

3.2 Experimental results

The experimental snapshots corresponding simulation show the initial (1), transitional (2-8), and final (9) forms of the gel(Fig. 6). Let θ be an angle between the tangential line of the gel at the free end and one of the fixing ends. First, the gel bent toward the anode side (2). A portion of gel near the free end started to bend in the other direction when $shape$ went over $\pi/2$ (3). The deformation of root portion remained same. Again, when θ went under $\pi/2$, a smaller portion of the gel near the free end started to bend the first direction (4). The polarity of the electric field was reversed at (5). Finally, the gel reached the desired shape (9).

3.3 Reachable wave-shapes

Different shapes were generated through alternating the performance functions. The performance functions of one-half-waved shape (f_1) and two-half-waved shape (f_2) are defined as same as that of the three-half-waved shape.

$$f_1 = \theta_0 - \theta_1 \tag{6}$$

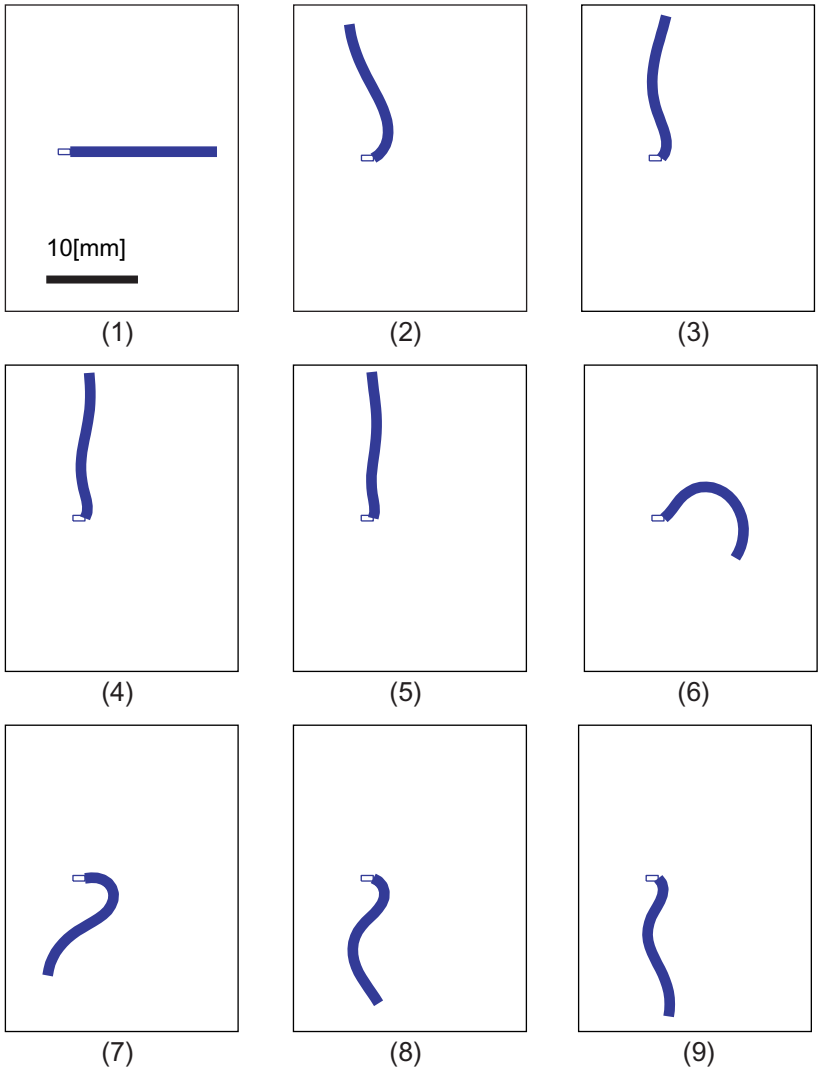

Fig. 5. Simulated process of the gel which deforms into three-half-waved shape

$$f_2 = (\theta_{\frac{1}{2}} - \theta_0) + (\theta_{\frac{1}{2}} - \theta_1) = 2\theta_{\frac{1}{2}} - \theta_0 - \theta_1 \tag{7}$$

The input sequesnces which maximize the performance functions were obtained. One-half-waved shape was generated by (1100011) with 90 secondes time interval. Likewise, two-half-waved shape was generated by (11111000) with 90 seconds time interval. Simulated and obtained shapes are shown in Fig. 7.

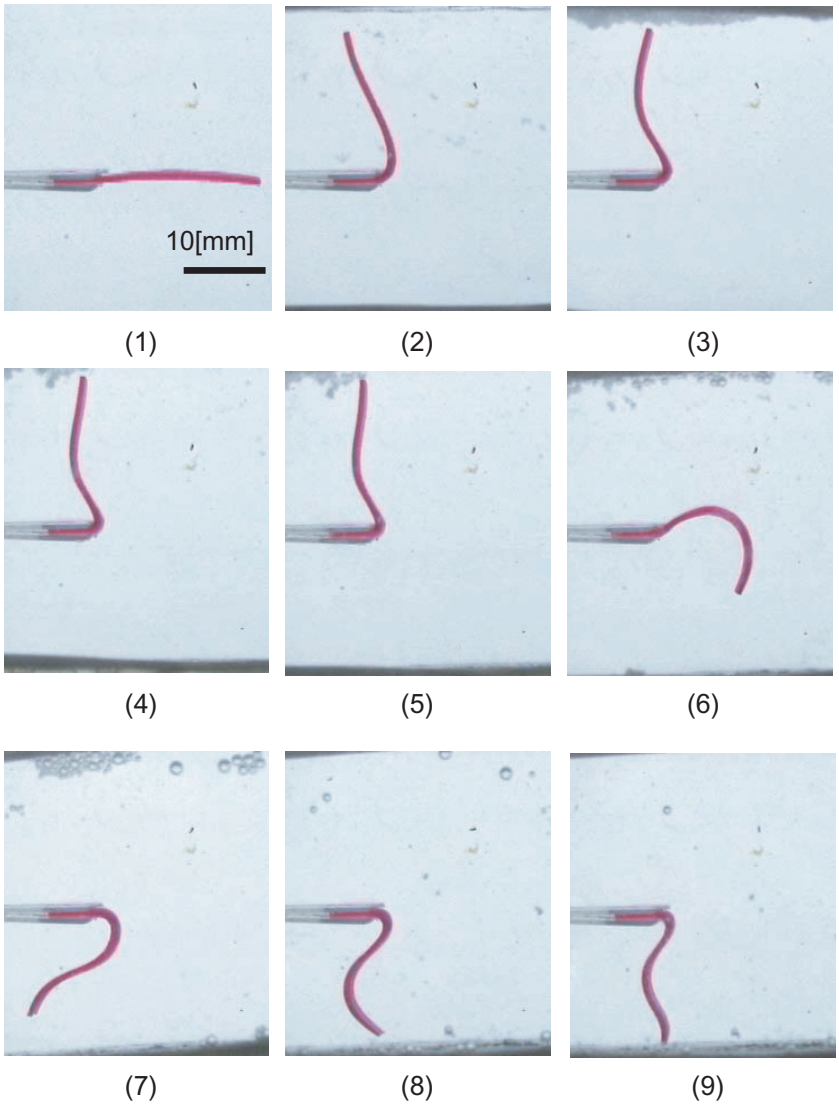

Fig. 6. Experimental results of the gel which deforms into three-half-waved shape

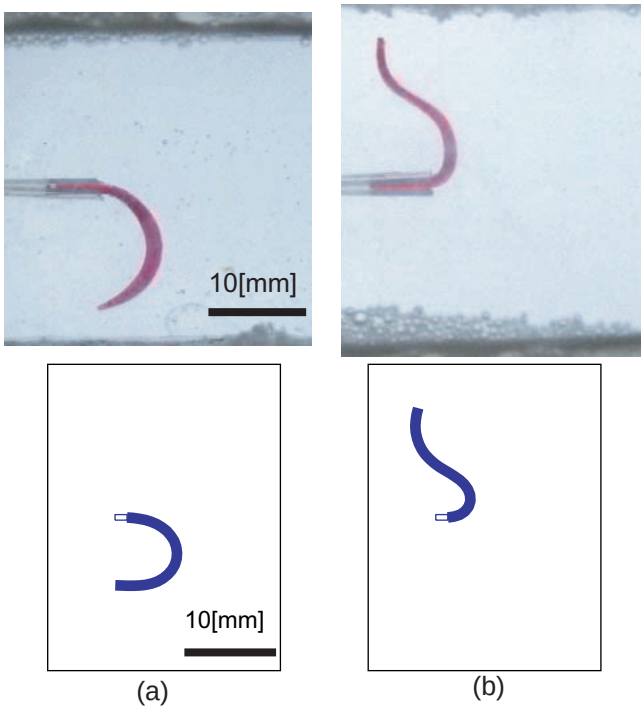

Fig. 7. Simulated and experimental results of the gel which deformed into (a)one-half-waved shape and (b)two-half-waved shape

4 Conclusion

The conclusions of this paper are summarized as follows:

1. Wave-shape pattern formation of a surfactant driven ionic polymer gel in a uniform electric field was described. A beam of ionic gel in a uniform electric field develops wave form through penetration of the surfactant solution.
2. The wave-shape pattern control method was proposed. Wave-shaped gels with varying curvature were obtained by switching the polarity of a spatially uniform electric field: 1) The period for reversing the polarity was explored through numerical simulation; 2) The performance function was defined with the tangential angle of the gel for determinating input sequence; 3) The period for reversing the polarity of the electric field was regulated when the numerical simulations are applied to experiments.
3. The method was experimentally verified. Originally straight-shaped gel deformed into the shapes containing one, two and three half-waves.

Further investigation is required in order to make clear the reachable shapes by this method. Polarity switching of spatially varying electric fields would generate

more complex shapes. From the mechanism of deformation and experimental results, we can consider gel as an integrator of the series of input. Molecules are adsorbed on the surface of the gels, which deform the shape of the gels. The deformed surface forms a reaction field in the next step. In this way, series of input by a time varying electric field are accumulated. Hysteretic property of the materials helps to solve the degrees-of-freedom problem of deformable robots containing electroactive polymers.

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