Kinematics of Gel Robots made of Electro-Active Polymer
PAMPS Gel

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Abstract
This paper introduces and describes a novel kinematic model based on chemical reaction to control robots made of soft materials, poly (2-acrylamido-2-methylpropane sulfonic acid) gel (PAMPS gel). Experiments were conducted using a prototype mechanism whose energy is supplied by applying an electric field in a surfactant solution. We have verified the validity of our model by comparing the experimental and simulation results obtained by bending a flexible strip of PAMPS gel under a uniform electric field.

1 Introduction
Soft materials which generate force and change shape can potentially form a basis for the development of artificial muscles. Electro-active polymer (PAMPS) gel is one such promising material. Most studies have focused on analyzing the material properties of the gel. However, it is not yet clear how to design effective shapes or to control various shapes of materials dexterously. It is difficult to apply the conventional methods used to control rigid, articulated mechanisms for controlling gels because the material is too elastic and conceptually has infinite DOF. The purpose of this study is to examine how to control gel robots. Gel robots are made entirely of gel material and can be regarded as complexes of artificial muscles. We previously reported a gel robot design using thin parts of the material as actuators and thick parts as structures[1]. In this paper, we propose the kinematic model of gels based on chemical reaction, which can be applied to a variety of shapes of gel robots using various kinds of control signals.

1.1 Electro-Active Polymer
Over the past few decades[2] a considerable number of studies have been made on artificial muscles made of chemomechanical polymer. Among them, electro-active polymers are currently the promising materials. However, a material with characteristics comparable to a real muscle does not yet exist. If the application is fixed and one of three material properties is critical among force, displacement and response speed, specific materials can be selected.

For example, if large forces are expected: piezoelectric polymers or electrostrictive polymers are appropriate [3][4]. If large displacements are important, gels [5][6][7] or conducting polymers are suitable. [8][9][10]. If high speed response is required, then ion conducting polymer composites are preferred [11][12][13][14].

Because we focus on shape control, we have selected electro-active polymer gel, Poly (2-acrylamido-2-methylpropane sulfonic acid) gel (PAMPS gel) [5][15] which is capable of large deformations although the response speed is not so fast. The main advantage of this material is transformation can be halted if required while most of materials are difficult to keep their controlled shape because of their driving mechanism.

1.2 Gel Robots
The purpose of this study is to present a method to design full body elastic robots similar to sea anemones, sea cucumbers, or jellyfish. The robots are made entirely of gel. Without any rigid structure, they can easily bend, fold, move, or change shape. They can manipulate external objects without causing damage to the object or themselves. To realize a robot with a functionality comparable to one of the sea creatures described above, we make an attempt to construct a robot body made entirely of "gel".

We shall refer to a “Gel Robot” as a controllable mechanism whose body is made entirely of chemomechanical polymer gel. A conventional robot typically consists of controllers, sensors, actuators and struc-
tures, but here our discussion is limited to actuators and structures. In order to remove the effects of wires and focus on the relationship between shape and function, a gel robot will be initially controlled by electric fields. Prototype gel robots were developed using thin parts as actuators and thick parts as structures. Examples include a sea butterfly robot that swims in the solution (Figure 1, left top), a shrimp robot (Figure 1, right top), a lizard robot (Figure 1, left bottom), and a seaweed robot (Figure 1, bottom right). The question we must consider here is how to connect chemical theory to control theory, since the deformation of gel material is driven by chemical reactions. First we focus on direct kinematic models which have not yet been established. There is linear approximate model[12] and continuum mechanics model[13] of other electroactive polymers, but there is no discrete model based on chemical reaction which is applicable to complex shaped gel robots.

To design the shape of a gel robot, it is very important to understand the mechanism how chemical energy is converted to mechanical energy in PAMPS gel systems [5][16]. When an electric field is applied to a sheet of PAMPS gel, in a surfactant dodecylpyridinium chloride (C_{10}PyCl) solution containing sodium sulfate, the gel exhibits significant and rapid bending toward the anode. If the polarity of the electric field is altered repeatedly, the gel sheet exhibits oscillatory motion. This phenomena is based on an electro kinetic molecular assembly reaction of surfactant molecules on the hydro gel [17] [18]. The gel network is anionic[19], so positively charged surfactant molecules can therefore bind to its surface. This causes anisotropic contraction which bends the gel towards the anode.

2 Materials and methods

A poly(2-acrylamido-2-methylpropane sulfonic acid, PAMPS) gel is prepared by radical polymerizations from a 1.0M solution of 2-Acrylamido-2-methylpropane sulfonic acid (AMPS), in the presence of 0.05M N,N'-methylenebisacrylamide (MBAA) and 10^{-3} M K_2 S_2O_8 at 323[K] for 24 hours [5]. After the polymerizations, the gel is immersed in a large amount of pure water to remove un-reacted reagents until it reaches an equilibrium state. The degree of swelling of the gel is 79. This number is determined as a weight ratio of the water swollen gel to its dry state. Then it is immersed in a dilute solution of the surfactant, n-dodecyl pyridinium chloride (C_{10}PyCl) containing 3×10^{-2} M sodium sulphate.

Using measurements performed in the solution, the experimental apparatus is as follows: A pair of pararell plate platinum electrodes (each plate is 25[mm] wide, 40[mm] long, 0.2[mm] thick) is placed in the cell with 30[mm] spacing between them. A strip of the gel is placed horizontally, with one side of the gel fixed and the other side left free. In this way, the oscillatory motion of the free end of the gel can be observed from top. Direct current voltage applied through the electrodes from an electric source using a function generator D.C. power supply and amplifier circuits is used to create an electric field. The deformation of the PAMPS gel is analyzed by utilizing a video microscope.

All experiments were carried out at a room temperature of 298[K]. The gel material is originally sensitive because it is an open system. It is not stable and affected by many kinds of environmental conditions such as temperature, pH, etc. Because of the above characteristic, the parameters of the material scatter. However, every time, the order is the same. Thus, each experiment was carried out several times and the nearest to the average data were selected.

3 Measurement Result

3.1 Generating Stress and Strain

We have developed a new method to measure fundamental relationships between the electric field, stress and strain. Specifically, the generated stress can be calculated by measuring the radius of curvature of the beam shaped material. Based on the theory of

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bending mechanism, an electric field drives surfactants to the gel surface. The surfactants bind to the gel and generate stress on the surface due to anisotropic contraction. Since the material is extremely elastic, a slight stress can cause a large overall deformation. Before clarifying the generated stress, observe Figure 2. The final shape assumed by the gel under a uniform electric field is shown. With voltages under 5[V], the strip bends slowly and stops at the equilibrium state. The surface curvature is uniform. With voltages over 5[V], the strip becomes perpendicular, and stops with small oscillation, which is a limit state. The surface curvature is not uniform.

Let us suppose that the radius of curvature is almost uniform at low voltages. Then the generated stress \( \sigma \) is given by the following equation with radius of curvature \( \rho_r \) (Figure 3), Young’s modulus \( E \), thickness of the beam \( h \).

\[
\sigma = \frac{Eh}{2\rho_r}
\]  

Calculated stress and strain are shown in Figure 4. Higher voltages generate larger stress. Even if the thickness is different, the generated stress is independent of the thickness. The order of generated stress ranges from \( 10^2 \) to \( 10^3 \)[Pa] when Young’s modulus is a \( 3 \times 10^4 \)[Pa].

3.2 Shape and voltage dependence on step response

The design parameters for gel robots include the shape and size of the gel, and magnitude of the applied electric field. To understand the relationship between these parameters and the overall deformation, step responses were measured. At first, thickness dependency is observed. The deformation responses using a step voltage output at 5[V] for a 13.5[mm] \( \times \) 5[mm] \( \times \) 1.2, 1.8, 2.9[mm] strip are shown in Figure 5. Both the bending speed and the maximum deformation showed dependency on thickness. Each strip deforms until the adsorption saturates. Due to the low voltage (5[V]), the thick one stopped bending prior to the vertical state, while the thin one bent until it became vertical to the electrode. This is because the generating stress \( \sigma \) on the surface is equal at the same time, the radius of the curvature of a saturation point \( \rho_r \) is proportional
to thickness $h$ according to Eq.(1). The deformation speed of the thin strip is faster than the thick one. It took about 100[s] to reach saturation point of the thickest one and its maximum displacement is 2[mm].

Next, the voltage dependency was observed. The deformation responses using a step voltage input at 4, 5, 6, 7[V] for the same strip (13.5[mm]×5[mm]×1.2[mm]) are shown in Figure 6. The electric current density is proportional to the input voltage. This is because the solution between the two electrodes works as a resistor, which means the higher the voltage, the faster the speed of binding becomes.

Each strip achieved maximum deformation at the same place. Quantities of the maximum binding surfactant are the same according to the surface area of the strip. Thus, the differences were primarily in the time taken to reach the maximum state.

4 Kinematic model based on chemical reaction

Experimental results show that the amount of the adsorbed molecules is the basic quantity which interfaces gels and the electric field. The deformation of gels is a result of surface shrinking caused by the binding reaction of the surfactant molecules with the polymer network[17]. For the purposes of theoretical analysis, the binding reaction can be characterized by two processes: an adsorption process and a propagation process (see Figure 7).

Adsorption Process: electrostatic salt formation

Propagation Process: hydrophobic interaction between the bound surfactant, which stabilizes the aggregate in such a way as to settle adjacent to the already occupied site along the polymer chain.

Based on this theory and our measurements, we propose the following kinematic model to control shape of gel. Initially, we concentrate on a two-dimensional model.

Suppose that gels are articulated links made of polymer chains. The $j$th link is formulated using the following parameters: position vector $r[j]$, orientation vector $v[j]$, thickness $h[j]$, adsorption state parameter $ads[j]$. The adsorption state parameter indicates whether the link is adsorbed by molecules or not. Based on this formulation, the gel is expressed as:

$$gel = [r, v, h, ads].$$

When the voltage is applied on the electrodes, the resulting 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. As the current density increases, the probability of binding rises. Thus, the adsorption process is generally expressed as follows:

$$ads[j] = f(v[j], i(r[j])) + g(ads[j]).$$

where $i(r[j])$ is the current density at $r[j]$. It is calculated from Eqs.(4,5)

$$i(r[j]) = \sigma E(r[j])$$


where $\sigma$ is the conductivity, $E(r[j])$ is an electric field, and $\phi(r[j])$ is an electrostatic potential, at $r[j]$. Here we propose specific instance of $f$ and $g$ in Eq.(3) as:

$$v_{ads} = -p_{ele}(v_\perp[j] \cdot i(r[j])) + p_{ads}ads[j],$$

where $v_\perp[j]$ is a vector perpendicular to the link, $p_{ele}$ and $p_{ads}$ are effect parameters of electric field and the previous state of adsorption. If $p_{ele}$ is large, the electric field produces large effects on the adsorption of the molecules. Once the surfactant molecules are adsorbed, it takes a long time to desorb without reversing the electric field. We express this phenomenon by setting $p_{ads}$ slightly smaller than 1.

The next step is the propagation process. The adsorption state affects the joint angle of each link and can be expressed generally as follows:

$$dv[j-1,j] = h(ads[j-m], \ldots, ads[j+m-1]),$$


Adsorbed molecules aggregate to each other causing the joint angles to change. For simplicity, Eq.(8) is expressed by Eq.(10), which means adsorbed molecules interact only with the molecules on the next link. The parameter, $p_{ads}$, calculates the joint angle from the adsorption state and the thickness of the gel.

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

Using Eq.(9) and the boundary condition, the orientation of each link is calculated. Then the positions are determined by Eq.(11) and the boundary condition. The boundary condition decides which side of the strip is fixed or left free.

$$r[j] = \sum_{k=1}^{j-1} v[k].$$

In order to evaluate the model, we simulated the behavior of a gel strip under a uniform electric field. The size of the gel and applied voltages are the same as some of Figure 5 and 6. We examined three cases (see Figure 8). (a) 1.2[mm] thick under 5[V], (b) 1.8[mm] thick under 5[V], (c) 1.2[mm] thick under 7[V]. The length of the strip is all 13.5[mm]. The parameters differ according to the link length $|v|=0.1[mm]$, the number of links 135, the time step 1[s], conductivity $\sigma=6.24[\text{mS/cm}]$, in this case $p_{ele}$ is 3.5, $p_{ads}$ is 0.99, $p_{dv} = 0.0065$. Comparing the results in Figure 5 and 6 the simulation gives good agreement with the experimental results. Simulated deformation stops suddenly because the model doesn’t consider the time delay of converting stress to strain. Each strip achieved maximum deformation at the same place under different voltages compared with (a) and (c). The maximum deformation showed dependency on thickness compared with (a) and (b).
5 Conclusion

We have presented a novel kinematic model to control robots made of soft gel materials. First, the stress and strain generated by the materials were estimated by measuring by radius of curvature of a beam shaped gel. Second, the thickness and voltage dependencies on the step responses of the gel were carefully examined. The amount of adsorbed molecules on the surface of the gel characterizes a system consisting of gels and an electric field. Considering these measurements and theory, we reported a new kinematic model. We evaluated the validity of our theoretical model by comparing the deformation of simulated and experimental results. The model gives a reasonably good approximation to step response under different applied voltages with different thickness of the gels This method is based on local interaction, and it can be applied to various shapes of gels and various types of electric signals. Thus, is can form a basis for formulating the kinematics of gel robots.

Key areas of future research include the following: examining ways to identify the parameters, and their physical and chemical meaning; to evaluate this method by applying a changing signal input or spatially varying electric fields instead of uniform one; applying this method to micro-scale size gels; The future direction of this study is to construct an inverse kinematics model based on the direct kinematics model proposed in this paper.

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