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Inverse Dynamics of Gel Robots made of Electro-Active Polymer Gel

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***Abstract*— This paper formulates and solves the inverse dynamics problem of deformable robots made entirely of electro-active polymer gel. One of the primary difficulties with deformable robots is that they have conceptually infinite degrees of freedom. We solve this problem through the selection of an essential point to generate a desired motion. The problem is then reduced to trajectory control of a point on the robot. We have proposed dynamic models of electro-active polymers system and derived a variety of motions by applying either spatially or time varying electric fields. However, the motion control problem has not yet been investigated. We show a procedure to realize an inversion (turning over) motion of a starfish-shaped gel robots by applying both spatially varying and time alternating electric fields. This work takes the first step towards motion control of deformable robots.**

I. INTRODUCTION

Electroactive polymers (EAP) are candidate materials for building artificial muscles. They generate stress and strain based on particular electrochemical reactions. Early artificial muscle materials were presented in the 1950s[1]. Since then, a variety of materials have been developed. The performance of EAP has improved rapidly during the 1990s. Generating stress, strain and response speed are comparable to animal muscles. Their problems are strength and durability, which limits the current applications. New devices have been constructed utilizing these materials: a micro robot[2] that can manipulate cells with conducting polymers[3]; tactile displays[4], catheters[5], and a propulsion mechanism[6] with ion conducting polymers, actuators of high power to weight ratio[7] with electrostrictive polymers[8].

Design and control methodologies, which is universal to these materials, are inevitable to realize deformable robots. Future applications of deformable robots are amusement and entertainment, manipulator for plastic surgery, and power assist suits that support the movement of human bodies. Purpose of our study is to investigate fundamental principle to design and control deformable robots like living animals by making use of artificial muscle materials. We explore ideas independent of particular materials and hopefully applicable to future materials, through using existing material.

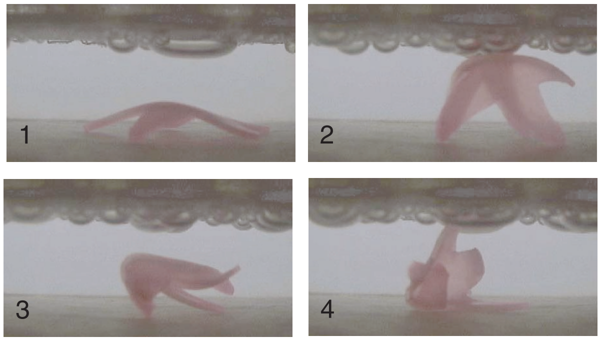

Fig. 1. Preliminary experimental results of a starfish-shaped gel robot that turns over

We have been prototyping robots made of EAP gels named ’gel robots’. We proposed a dynamic model[9] that describes both active and passive deformations of the gel. We conducted experiments using a spatially varying electric field generated by electrodes and derived methods for calculating the electric field. By combining the dynamic model of the gel and the electric field model, we have experimentally generated turn over motion of starfish-shaped robots [10] (Figure1), although the detail condition have not yet been investigated.

In this paper, we focus on turn over motion as an example to study motion control of deformable robots. One of the problem of deformable robots is that motion control is difficult because whose bodies have virtually infinite degrees of freedom. The point is to convert this ill-posed problem to well-posed problem. We decompose this problem into inverse dynamics problem considering the trajectory of the center of the robot.

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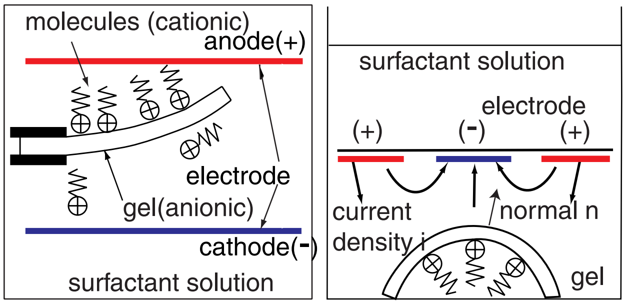


(a)pallarel electrodes (b)electrodes in a plane

Fig. 2. Mechanism of deformation of the gel

II. DYNAMIC MODEL OF THE GEL

Before solving the problem, we describe the dynamic model based on mechanism[9]. The model is used to design the experimental system, and investigate algorithm to control gel robots in the following sections. We describe the model in two steps. At first, we focus on active deformation caused by the interaction between the gel and electric field. Then we extend it to express both active and passive deformation.

A. *Modeling of active deformation*

We selected a typical electro-active polymer gel, poly (2-acrylamido-2-methylpropane sulphonic acid) gel (PAMPS gel)[11] [12] and its co-polymer gel from among the variety of electro-active polymers because its ability to undergo large deformations although the response speed is not so fast. The gel bends toward anode side in a surfactant solution when an electric field is applied.

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 between a polymer, and an electrochemical field including the solution and the electric field[13]. In this uniform framework (polymers and electrochemical fields), we model the active deformation. The deformation of the gel is a result of molecular adsorption[11] [14]. The cationic molecules which are driven by the electric field adsorb on the surface of the anionic gel [15]. Adsorbed molecules propagate and generate stress on the surface, which causes strain on the surface [16] (see Figure 2(a)). If we simply consider the gel as an articulated linkage made of polymer chains in two dimensional space, the gel is a collection of four components:

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

where the jth link is formulated using the 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. Then the adsorption rate at link j is expressed as:

$$vads = -p_{ele}(v_{\perp}[j] \cdot i(r[j])) + p_{ads}ads[j], \tag{2}$$

$$ads[j] = \begin{cases} 0 & (vads < 0) \\ vads & (0 \leq vads \leq 1) \\ 1 & (vads > 1), \end{cases} \tag{3}$$

with current density i on the surface of the gel r(Figure2(b)) and a vector perpendicular to the link, $v_{\perp}[j]$. This approximately represents the adsorption process: the electrical and chemical interaction. p_{ele} and p_{ads} are effect parameters of the electric field and the previous state of the adsorption. If p_{ele} is large, the electric field takes large effects on the adsorption of the molecule. Once the surfactant molecule adsorbed, it takes a long time to desorb without reversing the direction of the electric field. We express this phenomenon by setting p_{ads} nearly equals to 1. We can obtain the adsorption rate approximately by observing the joint angle of each link with a coefficient parameter p_{dv}:

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

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

In this way, we can reduce the complexity of the calculation. Even if the electric field is complicated, or the deformation of the gel is very large, we can approximate the deformation by substituting for the current density $i(r[j])$. The problem then reduces to one of obtaining the current density on the surface of the gel given the applied voltages at the electrodes. This is a kind of boundary-value problem. We can solve this problem numerically using the method we proposed via charge simulation [13].

B. *Modeling of both active and passive deformation*

In the previous model, we hypothesized that the gel is an articulated linkage in two dimensional space. To extend this model to describe dynamic motions of gel robots in three dimensional space, the model should also describe passive deformation caused by gravity force or contact with outer world. Therefore, we model gel as deformable objects. Several models are known to express deformable objects: a finite element model, a tensor-mass model, a mass-spring model[17]. The point of selecting the method is speed because we will use the model for motion control. And sure, the method should be applicable to large deformations. We use mass-spring model because of the above requirements.

When modeling the active deformation, the adsorption rate is directly substituted into the equation (2) that defines the deformation. If we consider that the stress is caused by a decrease in the rest length of each spring l_0 in the mass-spring model, then l_0 is a function of the adsorption rate. This is because the active deformation is caused by the stress generation on the surface of the gel. We approximate the adsorption rate as proportionally to the rest length of the spring

$$l_0 = l_{0init}(1 - p_l ads). \tag{6}$$

p_l is a parameter, which defines the effect of adsorption on shrinkage of the original rest length of the spring. l_{0init} is the initial length of the spring. We can obtain the parameter p_l by p_{dv}, considering that shrinkage of the spring causes a rotation of each link in the active deformation model.

C. Deformation in spatially varying electric field

We previously found that spatially varying electric field generated by multiple electrodes arranged in a planar array can drive free-ended gels [13], [10] (see Figure 2(b)). We describe the deformation in this configuration based on the model, because we use this configuration to drive gel robots. Initially, we placed a strip of gel material on the bottom of the water tank. Then we suspended multiple electrodes in a planar configuration 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 gel below the cathode electrode deforms into a convex shape as is shown in Figure 2(b).

III. EXPERIMENTAL SYSTEM

Experimental system is consisting of two parts, simulator and generator of the electric field. Input signal is common to simulator and generator, applied voltage data towards multiple electrodes. We implemented 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. If we set voltage data toward a set of electrodes, the generator converts the electric signals from digital to analog, amplify and generate the electric 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 voltages are controlled by a PC I/O board (RIF-01, Fujitsu) and amplified by amplifier circuits with a D.C. power supply (PAM35-20A, Kikusui). The transformation of the gel is analyzed by a video microscope (VH7000, Keyence), which is connected to video capture board (AD-TVK52Pro, AlphaData).

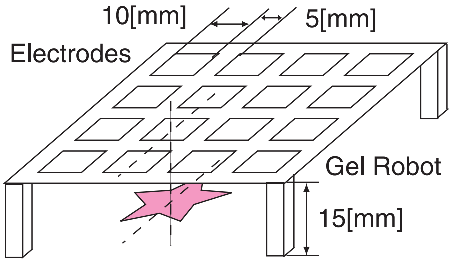


Fig. 3. The matrix of electrodes and starfish-shaped gel robot

To generate a spatially varying electric field to move gel robots, multiple electrodes are used. We arranged the electrodes to form a matrix of four rows and four columns in the same plane. There are total of 16 electrodes. The size of each electrode d_{ele} is 10[mm] square. The space between each electrodes d_{space} is 15[mm] (Figure 3). We created a starfish-shaped gel robot having five tentacles. The length of each tentacles is 6[mm] and the width is 6[mm] at the root and narrower at the tip. The gel robot is 15[mm] wide and 1[mm] thick. The gel robot is located under the matrix of electrodes, with the space between the gel robot and the array l being 15[mm].

IV. TURN OVER MOTION CONTROL OF A STARFISH-SHAPED GEL ROBOT

Now that we described deformation model of the robot and experimental system, we show our approach to realize turn over motion of a starfish-shaped gel robot. First, we describe the difficulty of the problem. Then, we decompose the problem into three parts. By the decomposition, the turn over motion control problem becomes simple inverse dynamics problem. Finally, we explain the experimental protocol and results.

A. Problem Statement

One of the primary difficulties is that the number of degrees of freedom is larger than the number of inputs, since deformable robots like gel robots have conceptually infinite degrees of freedom. One approach applies spatially varying electric fields generated by multiple electrodes, in this case, 16 electrodes in the same plane. However, in this configuration, we cannot control generating torque of each point directly.

Another difficulty is that there are numerous combinations of applied voltage time arrays for each multiple electrodes. A number of candidate input voltage arrays, in other words search space, is calculated as v^{nt}, with the number of input voltage value v, numbers of electrodes n, and numbers of time steps t.

Above difficulties come originally from deformability of the body, another one comes from the activeness of the materials. Typical problem for active materials is that

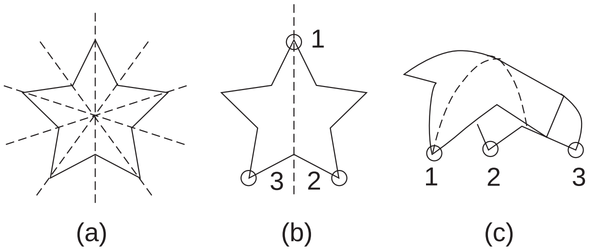


Fig. 4. Symmetry of starfish-shape

their properties scatter originally. Above all, gel is a sensitive material because it is an open system capable of exchanging matter and energy with outer world through polymer network. It is not stable and affected by many kinds of conditions like temperature, pH. Each gel robot responds in different speed even if we apply the same electric field. To control gel robots, we need to consider this characteristics.

B. Decomposition of the problem

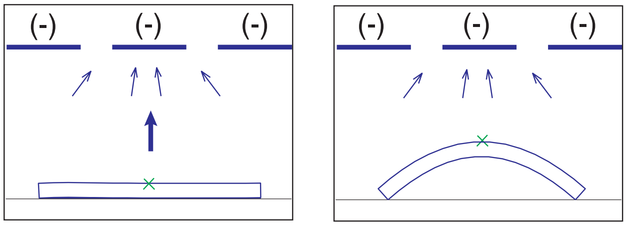
The above discussion suggests that, motion control of gel robots is not a simple problem if we formulate it in an ordinary manner. In this paper, we propose alternative method. If we get back to the objective of the motion, we do not have to control overall shape of the robot in each step. Our assumption is that only one or a few points are controlled by overall deformation of the other parts, which work cooperatively. We focus on the center position based on the preliminary experiment. If one observes the trajectory of the center of the starfish-shaped gel robot while it turns over, it lifts up and moves above the tip. The orientation of the center rotates and reversed in final state (Figure 1). This observation leads us to regard turn over motion as a kind of locomotion along with rotation.

In this manner, we can regard turn over motion control problem as inverse dynamics problem. The problem is then decomposed into three parts. The first problem is how to determine the direction of locomotion. The second one is to generate desired trajectory of the center of the robot along locomotion direction. The third one is to make the robot to follow the desired trajectory. The following subsections solve these problems.

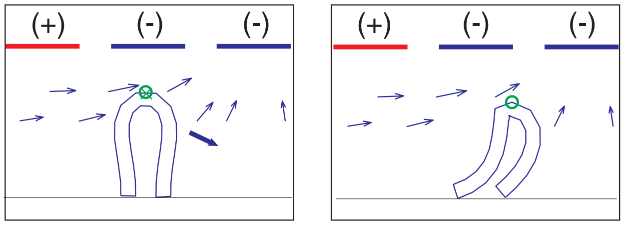
C. Direction of locomotion through symmetry analysis

To identify the potential direction of locomotion, we analyze the shape of the starfish at first. It is known that symmetry is a powerful way to measure machine that locomotes[18]. We examine the symmetrical aspect of the starfish-shape, in other words, pentagram. Pentagram is carried into itself by 10 kinds of operations; five rotations around its center, the angles of which are multiples of $2\pi/5$, and five reflections in the lines joining center with the five vertices (Figure 4(a)). We consider one from five axis of reflection, which will be extended to the rest of four axes.

The number of tips that slide on the ground is three, because three is a minimum number to support objects in the same plane. One of the sliding tips is on the axis of reflection, which we name tip 1 in Figure 4(b). Other two are facing to it across the center, which we name tip 2 and 3 in Figure 4(b). The directions of locomotion are along the symmetry axis direction. One is to move the center above tip 1, another is to move the one above tip 2 and 3 (Figure 4(c)). In summary, potential directions of turn over motion are 10, by two directions for each five axes.



(a) preparation process



(b) transition process

Fig. 5. Process of turn over motion

D. Trajectory generation of the center of gel robots

Now that we abstracted the nature of turn over motion and figuring out the potential directions of motion by symmetric analysis, let's move on to the desired trajectory generation.

Our strategy to generate objective motion in a simple manner is to divide the motion into two processes, preparation process and transition process. At preparation process, we apply the electric field to move the center upward and to make the distance smaller between the center and the tip along the ground(Figure 5(a)). At transition process, we switch the electric field so as to make the center rotates about the tip (Figure 5(b)).

Then, we prepared template patterns of applied voltage sequences along diagonal direction of matrix electrodes (Figure 6). Here we explain our procedure. Initially, starfish gel robot is placed below the electrode whose applied voltage is -E. The adjoining electrodes along the diagonal direction are also applied voltage -E, and other electrodes are applied voltage E (Figure 6(a)). Secondly,

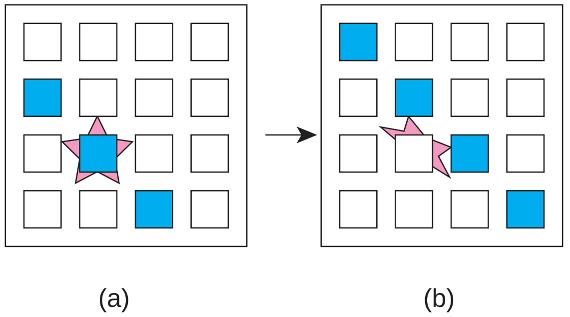


Fig. 6. Template patterns of applied voltages

we switch the patterns of voltages toward vertical to the diagonal direction, when orientation of the tip of the tentacle becomes vertical to the ground (Figure 6(b)). Then, gel robots turn over. We preliminary investigated the condition for switching the two processes. We found that the gel robot turns over in high reliability by switching the input when the orientation of the tip becomes vertical. At that time, the height of the center of the robot was 6.5[mm]. If the switching timing is earlier, the robot deforms back to the planer shape. In this way, desired trajectory and nominal input electric fields were generated simultaneously.

E. Design of servo controller

After trajectory generation of the center of the robots, the next step is to design servo controller to follow the desired trajectory. The difference between this problem and ordinary problem is that we cannot control the generating torque of the gel robots directly, because the electro-active polymer gels, which we use in this paper, are driven by separated electrodes and their torques are coupled. We need to regulate the input voltage, because the internal parameter of the gel scatters, as we stated in the problem statement. The effect parameters of the electric field p_{ele} ranges from 1.7×10^{-2} to 2.3×10^{-2} in equation (2). It is difficult to solve analytically since the constitutional equation (2) is highly nonlinear and the generating stress is coupled with spatially varying electric fields. We designed feedback controller with simulator numerically to work in the possible range of the parameters.

$$E = K_p(z - z_d) - K_v\dot{z}, \tag{7}$$

where E is the amplitude of the applied voltage to the electrodes, z is the position of the trajectory, K_p and K_v are position and velocity feedback gains. Typical values are $K_p = 10[V/mm], K_v = 0.5[Vs/mm]$.

V. EXPERIMENTAL RESULTS

To evaluate our approach, we carried out experiments for five times. Five times out of five the starfish-shaped gel

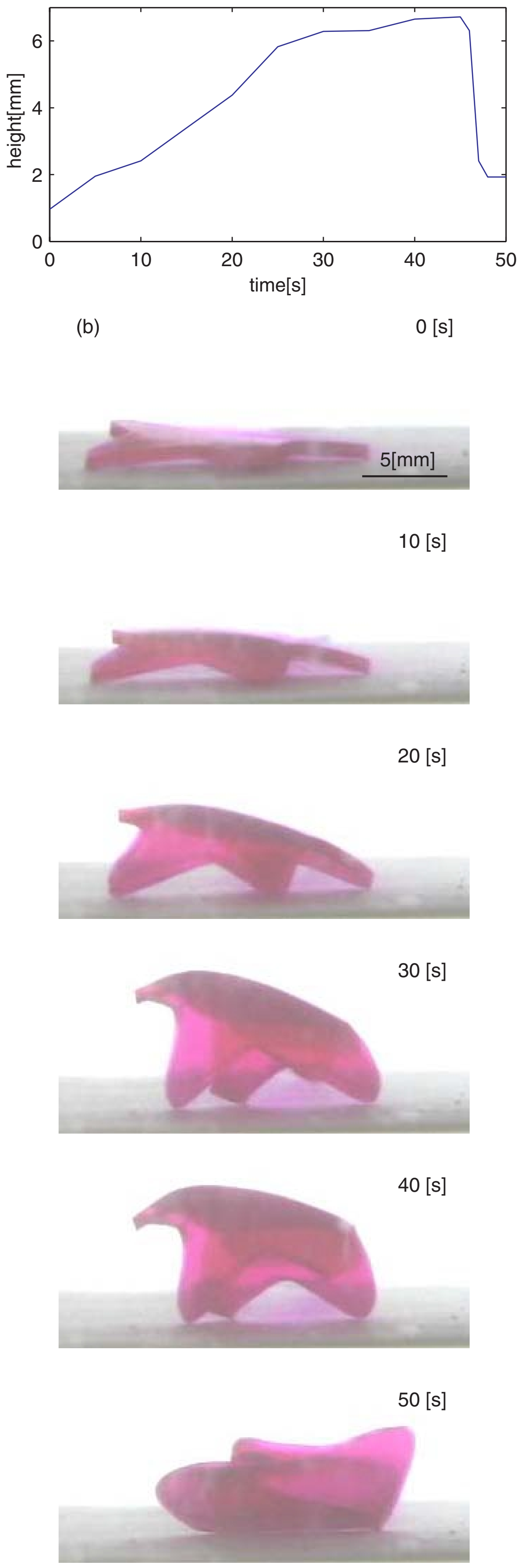


Fig. 7. Turn over motion of a starfish-shaped gel robots: (a) trajectory of the center of the robot (b) snapshots of the motion

robots successfully turned over. One of the obtained trajectory of the center of the robots is plotted in Figure 7(a). Figure 7(b) shows its snapshot of motion. The center of the robots reached the desired position during preparation process and switched to the transition process in 40[s], whereas transition process took 6 to 10[s]. The reason of these scatters comes from the instability of the transition process. Small difference of the center position leads difference of rotating speed during transition process.

VI. CONCLUSION

In this paper, we showed a method aimed at solving the motion control problem of deformable robots made of electro-active polymer gel. As a first step, we realized an inversion (turn over) motion of starfish-shaped gel robots. One of the difficulties in modeling deformable robots is that they have conceptually infinite degrees of freedom to control. We solved this problem through selecting an essential point to generate the desired motion, in this case, the center of the body. Then, the difficulty of the problem reduces to trajectory control of this point, which can be formulated as an inverse dynamics problem. We solved this problem in three steps: The first step is to select the direction of motion through symmetry analysis of the body. The second step is to generate the desired trajectory of the control point. The third step is to design a controller to follow the trajectory. This procedure to convert an ill-posed problem into a well-posed problem is universal, independent of a particular material, machine or motion. Future work includes generic motion control methodology through simulation and apply them to the real gel robots.

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VII. REFERENCES

[1] W. Kuhn and A. Kachalsky. Reversible dilation and contraction by changing the state of ionization of high-polymer acid networks. *Nature*, Vol. 165, pp. 514–516, 1950.

[2] E. W. H. Jager, O. Ingan*ä*s, and I. Lundström. Microrobots for Micrometer-Size Objects in Aqueous Media: Potential Tools for Single-Cell Manipulation. *Science*, Vol. 288, pp. 2335–2338, 2000.

[3] E. Smela, O. Ingan*ä*s, and I. Lundström. Controlled Folding of Micrometer-Size Structures. *Science*, Vol. 268, pp. 1735–1738, 1995.

[4] M. Konyo, S. Tadokoro, and T. Takamori. Artificial Tactile Feel Display Using Soft Gel Actuators. In *Proceedings of the 2000 IEEE International Conference on Robotics and Automation*, pp. 3416–3421, 2000.

[5] S. Sewa, K. Onishi, K. Asaka, N. Fujiwara, and K. Oguro. Polymer Actuator Driven by Ion Current at Low Voltege, Applied to Catheter System. In *Proc. MEMS 98*, pp. 148–153, 1998.

[6] M. Mojarrad and M. Shahinpoor. Biomimetic Robotic Propulsion Using Polymeric Artificial Muscles. In *Proc. 1997 IEEE International Conference on Robotics and Automation*, pp. 2152–2157, 1997.

[7] R. Kornbluh, R. Pelrine, J. Eckerle, and J. Joseph. Electrostrictive Polymer Artificial Muscle Actuators. In *Proceedings of the 1998 IEEE International Conference on Robotics and Automation*, pp. 2147–2154, 1998.

[8] R. Pelrine, R. Kornbluh, Q. Pei, and J. Joseph. High-Speed Electrically Actuated Elastomers with Strain Greater Than 100%. *Science*, Vol. 287, pp. 836–839, 2000.

[9] M. Otake, Y. Kagami, M. Inaba, and H. Inoue. Dynamics of Gel Robots made of Electro-Active Polymer Gel. In *Proceedings of the 2001 IEEE International Conference on Robotics and Automation*, pp. 1458–1462, 2001.

[10] M. Otake, Y. Kagami, M. Inaba, and H. Inoue. Behavior of a Mollusk-Type Robot Made of Electro-Active Polymer Gel under Spatially Varying Electric Fields . In *Intelligent Autonomous Systems 6 E.Pagello et al.(Eds)*, pp. 686–691, 2000.

[11] Y. Osada, H. Okuzaki, and H. Hori. A Polymer Gel with Electrically Driven Motility. *Nature*, Vol. 355, pp. 242–244, 1992.

[12] Y. Osada, H. Okuzaki, J.P. Gong, and T. Nitta. Electro-Driven Gel Motility on the Base of Cooperative Molecular Assembly Reaction. *Polym. Sci.*, Vol. 36, pp. 340–351, 1994.

[13] M. Otake, M. Inaba, and H. Inoue. Development of Electric Environment to control Mollusk-Shaped Gel Robots made of Electro-Active Polymer PAMPS Gel. In *Proceedings of the 2000 SPIE 7th International Conference on Smart Structures and Materials*, pp. 321–330, 2000.

[14] Y. Ueoka, J. P. Gong, and Y. Osada. Chemomechanical Polymer Gel with Fish-like Motion. *Journal of Intelligent Material Systems and Structures*, Vol. 8, pp. 465–471, 1997.

[15] J.P.Gong, T.Nitta, and Y. Osada. Electrokinetic Modeling of the Contractile Phenomena of Polyelectrolyte Gels -One Dimensional Capillary Model-. *J. Phys. Chem.*, Vol. 98, pp. 9583–9587, 1994.

[16] H.Okuzaki and Y. Osada. Effects of Hydrophobic Interaction on the Cooperative Binding of Surfactant to a Polymer Network. *Macromolecules*, Vol. 27, pp. 502–506, 1994.

[17] S. Gibson and B. Mirtich. *A survey of deformable modeling in computer graphics*. MERL, 1997.

[18] Marc H. Raibert. *Legged robots that balance*. MIT Press, 1986.