DOI: 10.1007/s12541-012-0247-4

An Auto-focus Lens Actuator Using Ionic Polymer Metal Composites: Design, Fabrication and Control

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KEYWORDS: Ionic polymer-metal composites (IPMC), AF (auto-focus) Lens Actuator, Off-line least square parameter estimation, PID-controller

Ionic polymer metal composites (IPMCs) are attractive smart materials. We propose an auto-focus (AF) lens actuator using IPMCs for cellular phones. In order to ensure stability, IPMCs were fabricated by using a plasma surface treatment and an ionic liquid solvent. AF lens actuator using IPMCs was designed to implement a large displacement and increased force by using a curved IPMCs. And the actuator had a structure with two springs to ensure stable AF actuation. Subsequently, a prototype AF lens actuator was fabricated. The parameters of the actuator were estimated from experimental data and a linear model of the AF lens actuator system. Then, a proportional-integral-derivative controller was designed, and the motion of the AF lens actuator was demonstrated through simulations and experiments.

Manuscript received: October 31, 2011 / Accepted: April 23, 2012

1. Introduction

Nowadays, almost all cellular phones have camera modules in them. A camera phone, which is a cellular phone with a camera module, is no longer a special device. As a result, the performance and functionality of camera modules have improved rapidly. A 0.3-megapixel camera phone was released in the early 2000s. Six years later, a 10-megapixel camera phone appeared on the market. Various studies on camera modules have been conducted to add functions to the cameras such as auto focus (AF), optical zoom, shutter control, image stabilization, and vibration-reduction functions.[1]

AF is one of the first additional functions that was added to camera phones. However, AF is not a new technology; it has been used in digital still cameras for several decades. AF is a feature of a digital still camera that allows it to obtain the correct focus on a subject automatically. For this, an AF lens actuator is required to move the lens in the camera. Digital still cameras use stepper motors as AF lens actuators. These motors were also used in early camera phones. However, steppers are physically large, relatively expensive, mechanically complex, noisy, and power hungry, and they are thus not ideal for camera phones. Voice-coil motors (VCMs) and piezoelectric motors are other options for AF lens actuators. VCMs are the most widely used AF lens actuator; they are small, cheap, simple to implement, quiet, and more power efficient than stepper motors. Figure 1 shows the structure of a conventional VCM for a camera module. The actuator is composed of two parts, one fixed and the other moving. The fixed part consists of a yoke, a permanent magnet, and a fixed base. The moving part comprises the lens, its holder, and the coil. When electricity flows in the coil, a Lorentz force is generated between the coil and a magnet, moving the lens glued to the spring. Piezoelectric motors are another more energy-efficient option, although they are expensive and have complex driving systems. However, as all electrical power for camera phones comes from a battery, energy efficiency is an important merit and is the reason that piezoelectric motors are occasionally chosen instead of VCMs.[2-6]

Ionic polymer–metal composites (IPMCs) are electro-active polymers that have many potential applications. IPMCs have many attractive characteristics, such as low driving voltage, large displacement, lightness, solidity, and flexibility. IPMCs work as efficient piezoelectric motors with low power consumption. Therefore, we selected an IPMC for the AF lens actuator in a camera phone. IPMCs consist of a ‘sandwich’ structure composed of three layers: a middle of polymer between two thin metal films. When electric current flows through the metals, cation migration occurs, and the IPMC is bent. Lee’s group researched AF actuator using IPMC. They designed it to implement a large displacement in low-power consumption by using an anisotropic plasma treatment. However, we considered a design to implement a large displacement and force by using an structural change. In the process,

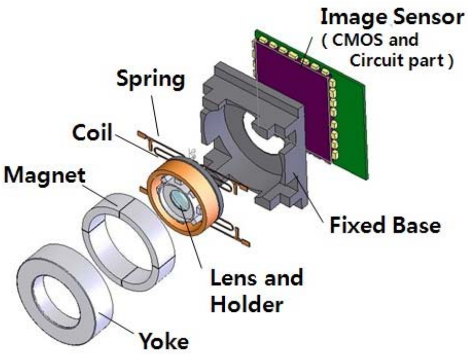

Fig. 1 Structure of a commercial AF lens actuator (VCM)

both a curved IPMC and a structure with two springs were developed. Subsequently, we fabricated a stable IPMC and a prototype AF lens actuator. The parameters of the actuator were estimated from experimental data and a linear model of an AF lens actuator system. Then, a proportional-integral-derivative (PID) controller was designed, and the motion of the AF lens actuator was demonstrated through simulations and experiments.[7,8,16]

2. Design of the IPMC AF lens actuator

As previously stated, VCMs are the most widely used AF lens actuators. As shown in Figure 1, the lens and holder are supported with springs. They are fixed by balancing the mass and the spring forces mechanically. This spring system has many advantages: it is simple, it moves without losses caused by fiction, and it is inexpensive. Therefore, we applied such a spring system to our IPMC AF lens actuator. Figure 2 shows an arrangement of four IPMC actuators located on each side of the moving part, which includes the lens. The springs act as a holder that can move up and down through the bending motion of the IPMC.

We considered two main points when the IPMC AF lens actuator was designed. First, we increased the generated force of the IPMC actuator by using curved material, as shown in Figure 2. The curved IPMC was simply a normal IPMC bent by a horizontal force (Fx). Figure 3(a) compares the normal (strip) and curved IPMCs. We used the experiment illustrated in Figure 3(b) to determine the characteristics of each IPMC. The strip IPMC was 3 mm wide, 9 mm long, and 0.3 mm thick. The curved IPMC was the same width and thickness, but it was 11 mm long. Figure 4 shows the force generated by the strip and the curved IPMCs. In the experiments, an input voltage of square waveform from ±1 Vp–p to ±3Vp–p was given. Outputs were measured at the load cell. At each input voltage, maximum force was acquired. The results indicate that the curved IPMC was more efficient. Second, we ensured stable actuation for the AF. To check the stability of the structure, a finite element method (FEM) analysis was carried out using the commercial software package ANSYS. According to the results, a structure with one spring was unstable. As shown in Fig. 5, the second resonance mode (122.55 Hz) was close to the first resonance mode (70.14 Hz). These neighbor modes can affect each other. The motion of first mode is controllable and second not. This motion should cause an

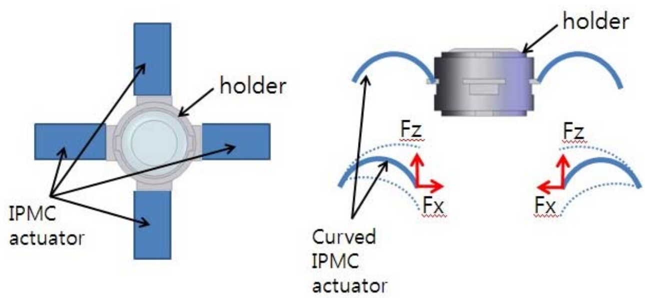

Fig. 2 Arrangement of four IPMC actuators and a curved IPMC

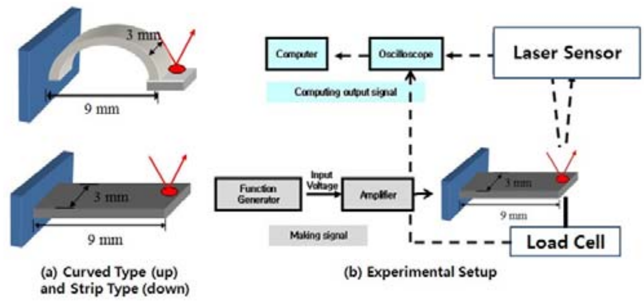

Fig. 3 Two types of IPMCs and the experimental setup used to determine their characteristics

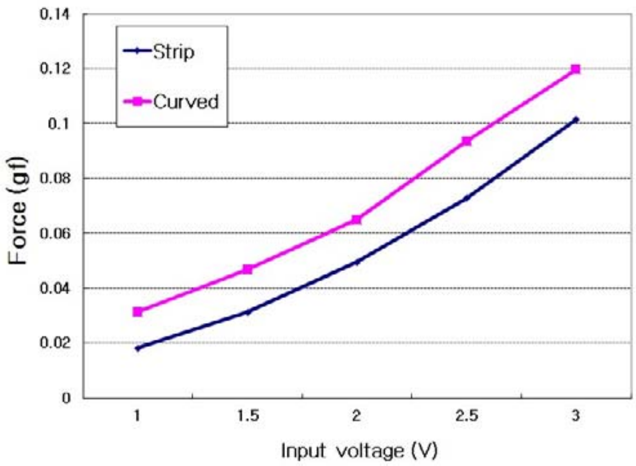

Fig. 4 Comparison of the force in the two types of actuators for the same 0.1-Hz input

aberration in the optical system. Therefore, we used a structure with two springs. Figure 6 shows that the first and second mode resonances occur at 175 and 2,000 Hz, respectively, which ensures a stable structure from a frequency response viewpoint. Additionally, the moving part of an AF lens actuator has a large height compared to its diameter because a minimum gap must be maintained between the three lenses to obtain a high-resolution image. A long moving part tilts easily, which can be prevented by using two springs.

The function of an AF lens actuator is to regulate the space between the lens and the image sensor according to the position of the subject to be photographed. Our optical system requires a maximum displacement of 160 μm and generates a maximum force of 800 mgf to satisfy these requirements within the limited space available.

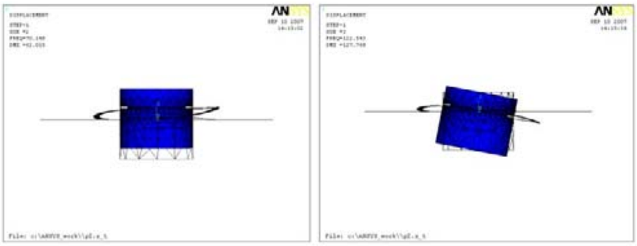

Fig. 5 Modal analysis of a one-spring structure from ANSYS

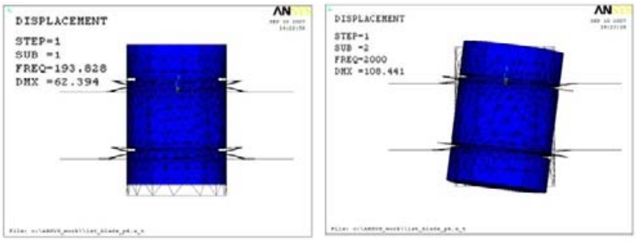

Fig. 6 Modal analysis of a two-spring structure from ANSYS

3. Fabrication and Experiment

3.1 Fabrication

We fabricated the IPMC through a basic manufacturing procedure that was established by Oguro.[9] However, some steps of the procedure were altered to offer increased stability. First, the solvent was replaced. Water is typically used as the solvent, but it evaporates easily in air and decomposes into hydrogen and oxygen gas at a certain applied voltage. If the solvent is lost, the IPMC cannot work. This is a serious problem for commercial electronic products. To resolve this problem, Bennett and Leo (2004)[11] presented an IPMC that used an ionic liquid as a stable solvent. We also replaced the water by an ionic liquid for the inner solvent. The ionic liquid was 1-ethyl-3-methyl imidazolium trifluromethane sulfonate (EMI-Im). Second, a plasma surface treatment proposed by Kim (2006)[10] was used to roughen the surface. This process not only increases the performance of an IPMC but also enhances its stability.

The IPMC was fabricated by following procedure.[9-11,16]

Step 1: O_2 plasma treatment or sand blasting was used to increase the adhesion between Nafion film and Pt.

Step 2: Pt ($[Pt(NH_3)_4]^{2+}$) was substituted for H^+ ($-SO_3H$).

Step 3: The amount of Pt absorbed by the Nafion film acting as an electrode was reduced by electroless plating.

Step 4: An electrode layer was added to reduce the surface resistance of the electrode.

Step 5: Counter-ion Li^+ was substituted for H^+.

Step 6: The sample was baked in a vacuum oven at high temperatures (75–85°C) and low pressures (25 Torr) for over 1 hour to remove water from the Nafion film.

Step 7: The solvent was replaced by immersing the sample in ionic liquid solvent (methanol (30–40wt%) + 1-ethyl-3-methyl imidazolium trifluromethane sulfonate) for 1–3 hours.

Step 8: A silicon film coating was added to prevent any loss of ionic liquid and provide more mechanical strength.

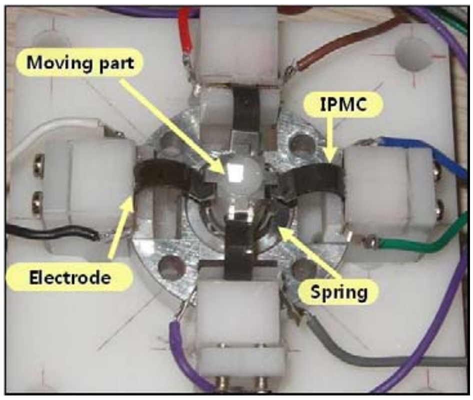

Fig. 7 Prototype AF actuator and experimental setup

This procedure allowed us to obtain more stable IPMCs for the AF lens actuator.

3.2 Prototype AF lens actuator and experimental setup

Figure 7 shows a prototype AF lens actuator using the curved IPMC. Figure 3(b) shows an experimental setup used to test the actuator. The generated displacement was measured by a laser sensor (KEYENCE LC-2440), and the measured displacement was transmitted to a digital signal processor (DSP) by an analog/digital (A/D) converter. The system was controlled by the DSP board. A control algorithm was programmed into the DSP using Simulink Matlab Control Desk. The control input was computed by the DSP. The driving voltage was applied to the designed actuator through an amplifier (OPA 541AP voltage follower) and was transmitted from the DSP by a digital/analog (D/A) converter. A resistor was connected to each actuator in parallel so that the power consumption could be determined by measuring the voltage applied to each resistor.

4. Control of AF lens actuator

Conventional camera modules acquire several images for a maximum stroke (160 um at this system) in preview mode and determine the best of the obtained images. And then the lens focus on an object to take the optimal image. Because the IPMCs had nonlinear actuation, In AF mode, it is necessary to control the actuator. we used the PID control which is a widely used controller in commercial area.

4.1 Modeling of the AF lens actuator

Figure 8 shows a block diagram of the entire system. The AF lens actuator can be divided into the IPMC actuator and the frame, which includes the moving part (lens and holder) and springs. The frame, including the entire system except the curved IPMC actuator, can be further divided into a non-linear part and a linear part. However, in this paper, the entire system was assumed to be linear for simplicity. By ignoring non-linearities and unknown factors, the AF lens actuator with two springs could be represented by a simple mass–spring system. The mass of the moving part was 0.3 g. The equivalent stiffness (3.64 gF/mm) was obtained by experiment, and

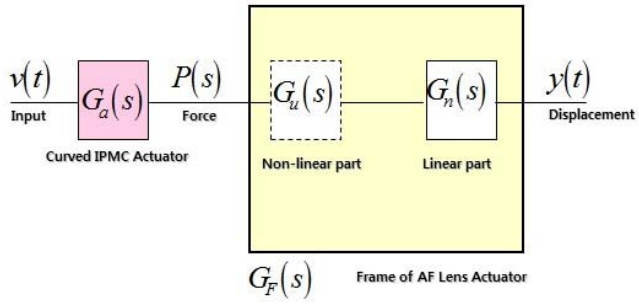

Fig. 8 Block diagram of the AF lens actuator

Table 1 Parameter of block diagram

$G_a(s)$	Curved IPMC actuator	Estimated
$G_n(s)$	Linear part of frame	Mass-spring-damper system
$G_u(s)$	Nonlinear part of frame	Ignored
$G_F(s)$	Frame of AF lens actuator	-
$G_p(s)$	Total system of AF lens actuator	$G_a(s) \bullet G_F(s)$
$G_c(s)$	Controller	PID controller

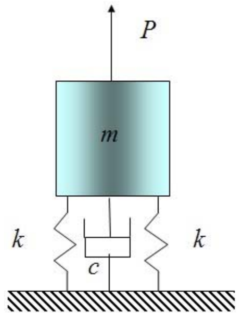

Fig. 9 Mass–spring–damper system

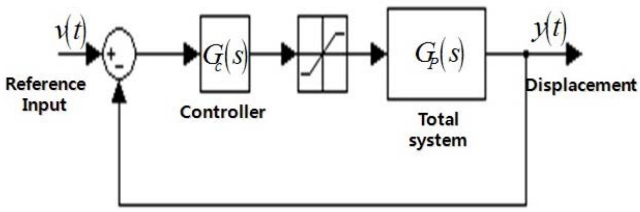

Fig. 10 Feedback system for the AF lens actuator

the damping ratio was assumed to be 2/3. Table 1 lists the system parameters, Figure 9 shows the mass–spring–damper system, and Figure 10 shows the feedback system.

4.2 Identification of the curved IPMC actuator

The transfer function for a frame was represented as a second-order system with assumptions. A transfer function for the curved IPMC actuator was obtained from experimental data. Since the input and output signals were measured in digital form over a given sampling time, corresponding to a single-input, single-output (SISO) system, the offline least squares parameter-estimation method was used to estimate the actuator parameters. For the estimate, the plant of the actuator was assumed to be a third-order linear system with one relative degree of freedom. An experiment using various voltages (1–3 V in 0.5-V increments) at 0.1 Hz was conducted to obtain the estimated parameters. As the input voltage affected the estimated parameters, a parameter-tuning procedure was executed after the estimation procedure to provide error compensation.

4.3 Offline least squares parameter estimation

The discrete form of a SISO system can be written as

$$y(k+1) = -\sum_{i=1}^{n} a_i y(k+1-i) + \sum_{j=0}^{m} b_j u(k-j) = \theta^T \phi(k), \qquad (1)$$

Where

$$\theta^T = [a_1,\ a_2,\ a_3,\ b_0,\ b_1] \qquad (2)$$

$$\phi^T(k) = [-y(k), -y(k-1), -y(k-2), u(k), u(k-1)] \qquad (3)$$

When the estimated output is defined by

$$\hat{y}(i) = \hat{\theta}\phi(i-1), \qquad (4)$$

the error between the real output and the estimated output can be written as

$$\varepsilon(i) = y(i) - \hat{y}(i). \qquad (5)$$

The least squares method is used to minimize the error and define the performance index,

$$J = \sum_{i=1}^{k} \left[y(i) - \hat{\theta}(k)\phi(i-1) \right]^2. \qquad (6)$$

Then, we can obtain two equations, which are batch formulae,

$$\hat{\theta}(k) = F(k)\sum_{i=1}^{k} \phi(i-1) y(i) \qquad (7)$$

$$F(k) = \left[\sum_{i=1}^{k} \phi(i-1)\phi^T(i-1) \right]^{-1}. \qquad (8)$$

The parameters are estimated by solving Equations (7) and (8).[13]

4.4 Estimating the actuator parameters

The transfer function of the curved IPMC actuator was estimated using the offline least squares parameter-estimation method with parameter tuning. The estimated transfer function was

$$G_a(s) = \frac{-0.3701s^2 + 24.65s + 611.5}{s^3 + 113.1s^2 + 4.533e004s + 2.348e004}. \qquad (9)$$

4.5 Feedback-control simulation and AF lens actuator experiment

The open-loop P-control technique is generally used for AF lens actuators. However, an inherent error is present in our system because the entire system was assumed to be linear for simplicity. A PID feedback-control system, which is one of the most common linear control techniques, was used for position control, as shown in Figure 10. As an IPMC cannot work at a limited voltage, a saturation function was used. In this optical system, to capture the optimal image while in AF mode, the lens must be moved to 160 μm from the initial position. The reference input consisted of eight steps; the first was 0.02 mm, which was maintained for 5 seconds.

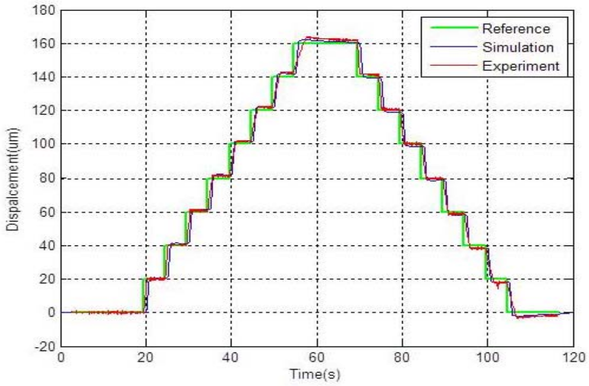

Fig. 11 Simulation and experimental results of the AF lens actuator

In each step, camera modules acquire 8 images moving 160 um. The PID controller was designed to satisfy these conditions. Figure 11 shows the controlled motion of the AF lens actuator along with the control input, which was obtained by simulation and experiment.

5. Conclusion and Future Work

A curved actuator using IPMCs and an AF lens actuator for a camera is proposed. A curved IPMC actuator was fabricated, and its parameters were estimated from experimental results using the offline least squares parameter-estimation method. For simplicity, the AF lens actuator was assumed to be a linear system that could be represented as a mass–spring–damper system. Based on the estimates, a PID controller was designed for position control, and the controlled motion was tested using both simulations and experiments. The controller motion followed the reference values due to saturation and moved upward a maximum distance of 160 um. Currently the total auto focusing time is less than one second in a commercial phone. The performance of IPMCs should be improved to decrease their response time and increase the efficiency of the proposed AF lens actuator. This will be examined in future research.

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