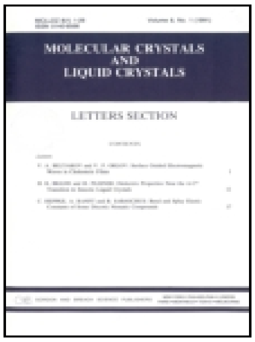

Molecular Crystals and Liquid Crystals

ISSN: 1542-1406 (Print) 1563-5287 (Online) Journal homepage: http://www.tandfonline.com/loi/gmcl20

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Marenori Kawamura & Shunsuke Ishikuro

To cite this article: Marenori Kawamura & Shunsuke Ishikuro (2015) Feature Extraction from Multiply Focal Images by Using a Liquid Crystal Lens, Molecular Crystals and Liquid Crystals, 613:1, 51-58, DOI: 10.1080/15421406.2015.1032038

To link to this article: http://dx.doi.org/10.1080/15421406.2015.1032038

Published online: 06 Jul 2015.

Mol. Cryst. Liq. Cryst., Vol. 613: pp. 51–58, 2015

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2015.1032038

Feature Extraction from Multiply Focal Images by Using a Liquid Crystal Lens

MARENORI KAWAMURA* AND SHUNSUKE ISHIKURO

Graduate School of Engineering and Resource Science, Akita University, Akita City, Japan

Three-dimensional imaging system in combination with a digital image processing is developed for determining all-focused and depth mapping properties by using a low-voltage-driving liquid crystal lens with a variable focal length. The continuous focused photo images without the magnification and reduction are taken by applying voltages to the electrodes of the LC lens and tuning a focal plane in a depth direction. The sharp and clear all-focused image can be obtained by processing an image digital filter from continuous focal images. The depth mapping properties can also be derived by our technique.

Keywords Three-dimensional imaging system; liquid crystal lens; variable focal length

1. Introduction

When three-dimensional (3D) objects are observed by using a camera system, the focused and defocused images can be obtained in same area. It is remarkable that the effect of focused and defocused images depends on the magnification of the objective lens since a depth of field is inversely proportional to the numerical aperture of the lens. There are many algorithms for estimating depth properties of arbitrary objects by moving in the depth direction to obtain continuous object images [1, 2]. When the positions of the camera or the object is moved in the depth direction to focus on the object with a mechanical focusing system, long acquisition times and the associated focusing errors due to the vibration are occurred.

Many types of optical devices by using nematic liquid crystal (LC) materials with a large birefringence and dielectric anisotropy have been developed. Various LC lenses with a tunable focal length without any mechanical movements have been reported by S. Sato [3, 4]. The focal length can be varied by controlling a refractive index profile of the nematic LC cell. A radially-varying refractive gradient-index distribution can be realized by the LC molecular reorientation which is caused by axially symmetrical electric field. The LC lens has a very wide range of the focal length from the negative to positive lens properties and preserves its optical quality over an entire focal range by applying two electrodes of the control electrode and circularly-hole-patterned electrode. When the circularly hole-patterned electrode of the LC lens is divided into four or eight parts and the different

*Address correspondence to Marenori Kawamura, Graduate School of Engineering and Resource Science, Akita University, 1-1 Tegatagauen-machi, Akita City 010-8502, Japan. E-mail: kawamura@gipc.akita-u.ac.jp

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voltages are applied to the divided electrodes, the effective refractive index distribution can be changed and then the focal plane can be moved; that is, a beam-steering property in addition to the beam-focusing property can also be obtained [5 ∼ 7].

In this study, we propose a three-dimensional imaging system for tuning a focal plane in a depth direction by using a composite objective lens with an LC lens without any mechanical movements. The focal length of the imaging system is controlled by applying the voltage to electrodes of the LC lens. The continuous photo images are taken by changing the position of the focal plane. The all-focused images and depth mapping properties of the sample target are obtained by processing with our proposed image digital filter from continuous focal images.

2. Imaging Camera System with an LC Lens

Figure 1 shows a 3D imaging system with an LC lens. The imaging system consists of a CCD camera, video lens, LC lens and polarizer. The polarizing direction of the polarizer is parallel to the rubbing direction of the LC lens. The images are continuously taken when each voltage is applied to the electrodes of the LC lens. Figure 2 shows the top and side views of the LC lens. This LC lens consists of a top glass substrate with a hole-patterned transparent electrode (thickness: 1.1 mm), isolated polymer film (5 μm), highly resistive film, LC layer with a parallel alignment, and lower glass substrate with the transparent electrode. The top patterned electrodes are fabricated by a photolithography technique and the diameter of the aperture is set to be 6.0 mm.

The surfaces of the highly resistive film and transparent flat electrode on the bottom substrate were coated with a polyimide parallel alignment material by using a spin coater. The glass substrates were baked in an electric oven at the temperature of 180°C for 1 hour. The surfaces of the polyimide film were rubbed along x-axis by using a rubbing machine. For rubbing the polyimide film, a rotating rubbing wheel with a cloth surface was applied to the sample surface coated with the polyimide film using a contact compression. Two substrates were overlapped at anti-parallel rubbing directions. The cell gap was controlled by using glass ball spacers at the diameter of 40 μm. The LC material of MLC-6080 (Merck Co.) was injected into the empty LC cell under the room temperature. Sine wave voltages (V_1 and V_2) at a frequency of $f = 1$ kHz were applied to the circularly hole-patterned electrode and central circular electrode of the LC lens respectively by using a function generator (WE7000, Yokogawa Co.). The LC lens can be operated by applying the voltage to the electrodes below 6 V.

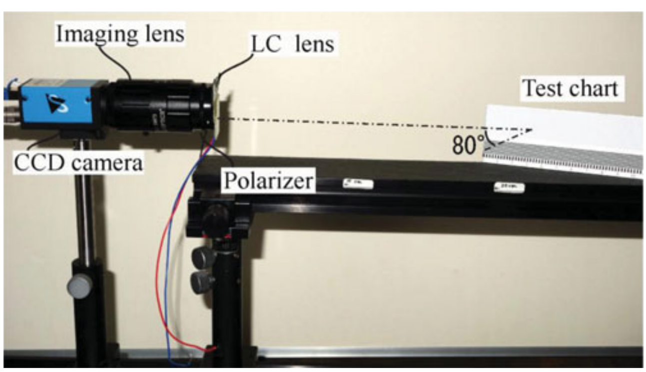

Figure 1. Imaging system.

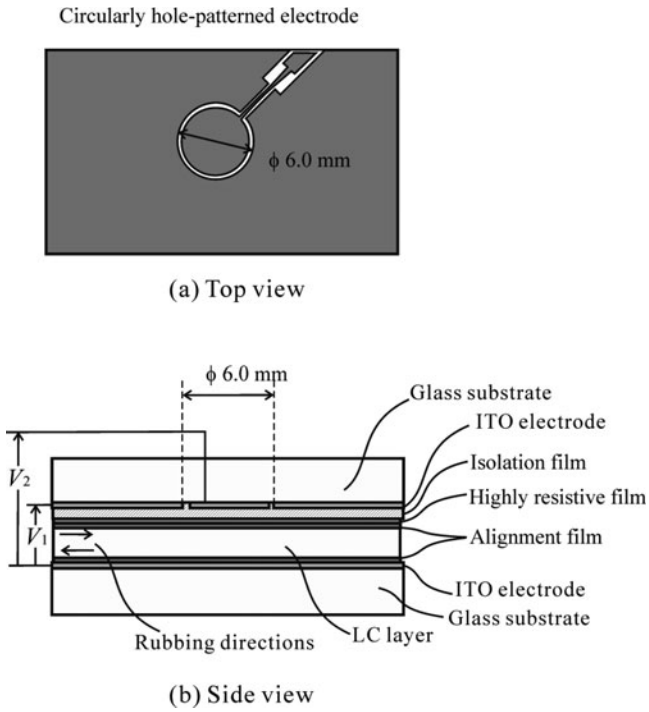

Figure 2. Structure of an LC lens.

The focal length of the LC lens can be estimated by measuring a circular interference fringes of an aperture of the LC lens under cross polarizers and fitting an optical phase difference along *y*-axis with a quadratic function derived from the interference fringe. The position of the focal plane can be controlled by applying the voltages V_1 and V_2.

The test chart is used for evaluating the spatial resolution of our system's ability to distinguish object details. A modulation transfer function value, such as the contrast ratio between the dark and bright areas can be determined by measuring the light images from the equal bars of the spatial square wave targets.

3. Imaging Camera System with an LC Lens

Figure 3 shows an object of unknown shape placed on the translation stage. The reference plane corresponds to the initial position of the stage. The configuration of the video lens, an LC lens and imaging sensor defines a single plane. The distance (d_f) between the focused and reference planes is determined by measuring the focal length of the LC lens when the voltages are applied to the electrodes. The photo images ($I_1 \sim I_k$) of the object can be continuously scanned step by step with a constant change of the focusing distance between consecutive images. The integrated image $I(x, y)$ with a deep depth of field (DOF) in objects may be expressed as:

$$I(x, y) = \sum_{i=1}^{k} I_i(x, y)\, S_i(x, y), \tag{1}$$

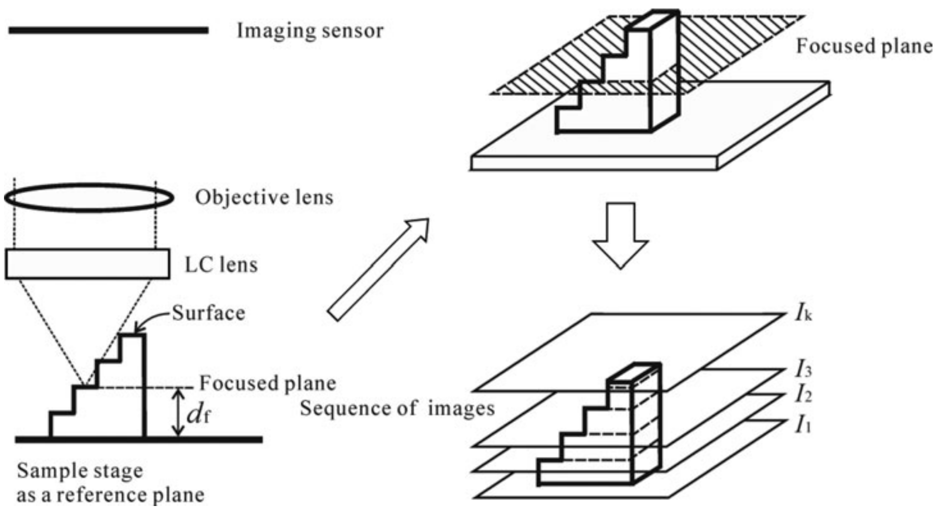

Figure 3. Focused plane on an unknown shape.

where $i = 1, 2, \cdots k$ and k is the number of the images in the sequence. $I_i\,(x, y)$ is the light intensity at a pixel position (x, y) for the i^{th} image in the sequence and $S_i\,(x, y)$ is a sampling function at the same pixel position. The position of the exactly focused point can be obtained by determining $S_i\,(x, y)$ from consecutive focal images of the objects.

The well-known digital image filter [8] in this study is given by

$$V_i(x, y) = \frac{1}{W} \sum_{p=-Wx}^{Wx} \sum_{q=-Wy}^{Wy} \left\{ I_i(x+p, y+q) - \overline{I_i}(x, y) \right\}^2, \tag{2}$$

where $\overline{I_i}(x, y) = \frac{1}{W} \sum_{p=-Wx}^{Wx} \sum_{q=-Wy}^{Wy} I_i\,(x+p, y+q)$ and $W = (2Wx+1)(2Wy+1)$ is a specific region such as a window around the pixel of interest. The position of the focused point can be obtained by the variance at the specific region.

The consecutive photo images are taken by adjusting the focal length and then the three-dimensional distributions of the focused images are reconstructed by the image filter processing as already described in the equation (2). We developed this image filtering process by using a Laboratory Virtual Instrumentation Engineering Workbench (Labview) from National Instruments Co. with a vision/image processing development software.

4. Results and Discussion

The focal length of the composite lens with the video lens and LC lens can be estimated by moving the target along optical axis and focusing the test chart such as a Ronchi ruling target with the spatial frequency of 0.5lp/mm. Figures 4(a) and 4(b) show focal length properties of the composite lens when the voltages V_1 or V_2 at the frequency of 1 kHz above the threshold voltage of 1.6 V are applied to the circulary hole-patterned electrode or central circular electrode. The focal length is 25 cm when voltage V_1 and V_2 are 0 V. As increasing the voltage V_1 and $V_2 = 0$ as shown in Fig. 4(a), the focal length decreases from 25.0 cm to 18.2 cm since the LC molecules at the edge of the aperture begin to reorient along the nonuniform electric field caused by the circularly hole-patterned electrode and then the

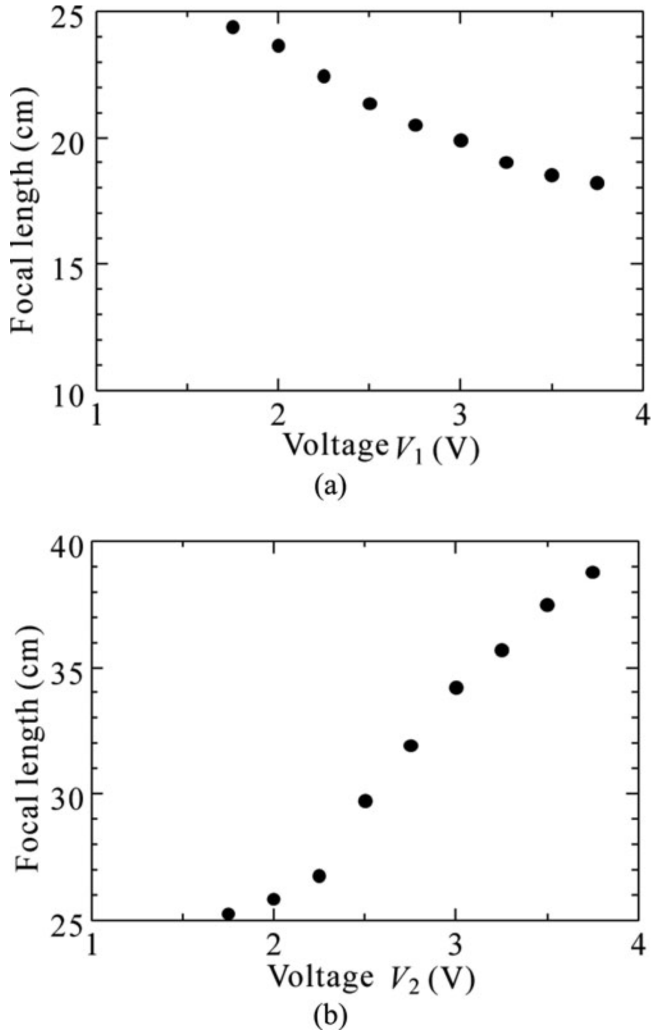

Figure 4. Focal length properties.

focal length of the LC lens becomes shorter. On the other hand, as increasing the applied voltage to the central circular electrode [Fig. 4(b)], the focal length of the composite lens varies from 25.0 cm to 38.8 cm since the LC molecules are orientated at around the center of the hole-patterned electrode along the nonuniform electric field and then the focal length becomes longer. The focal length of the composite lens varies from 18.2 cm to 38.8 cm; that is the range of the total focal length is 20.6 cm by arranging the applied voltages V_1 and V_2.

The distance between the composite lens and the sample target is fixed and the focal length is adjusted with applying the voltage to the LC lens. The thirty continuous photo images of the sample target which is tilted at 80 degrees with respect to the optical axis are taken by the CCD camera when the position of the focal plane along the depth direction is operated from about 25.0 cm to 37.0 cm. The position of the focal plane along the depth direction is changed every 0.4 cm by using the programmable controller. Three photos are

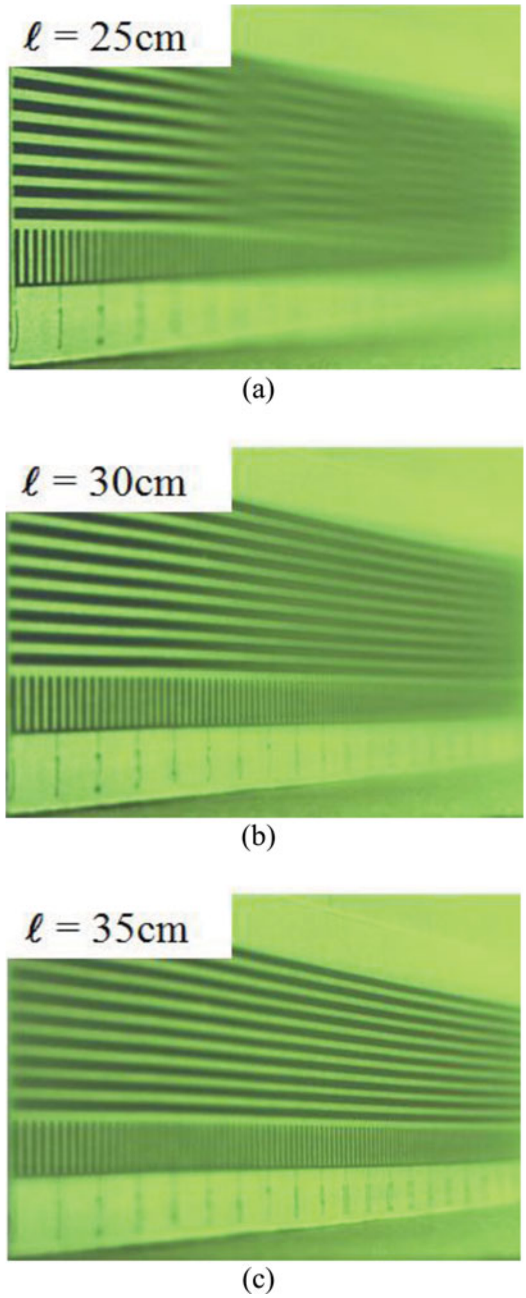

Figure 5. Images at different focal planes.

selected as shown in Figs. 5(a) ~ (c). Both the magnification and reduction of these images cannot also be obtained.

Figures 6(a) and (b) show the all-focused image and the depth mapping image of the tilted sample target at 80 degrees by using our proposed image digital filter from continuous 30 focal images. The color bar shows the depth scale from 0 cm to 12 cm. The sharp and

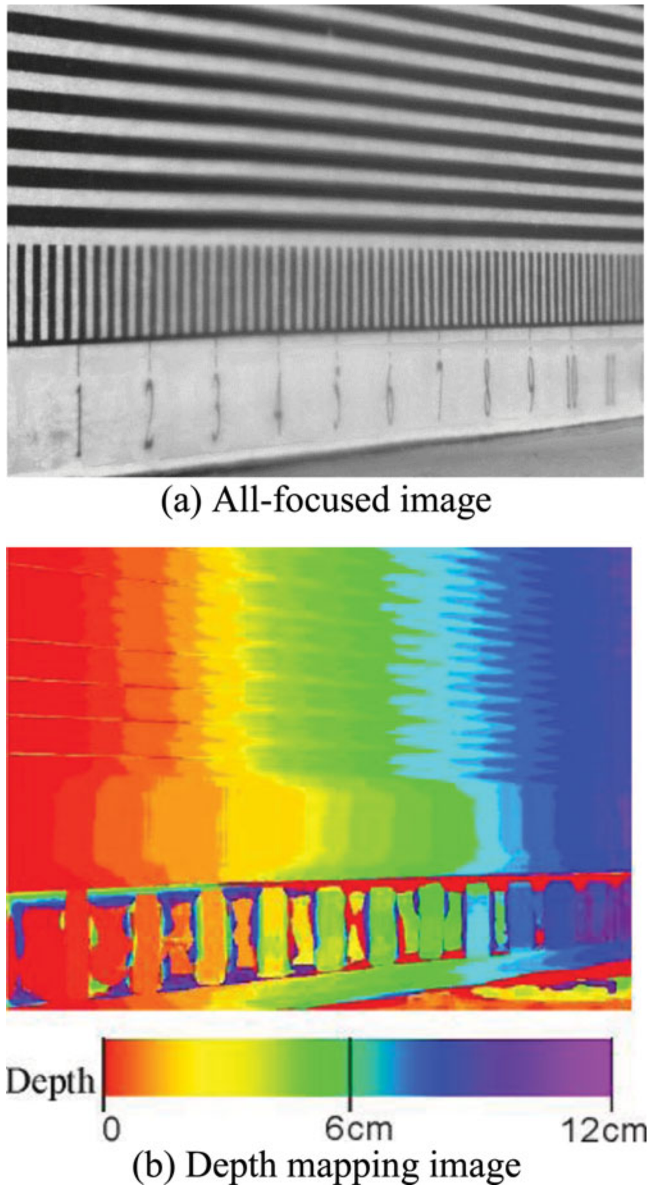

Figure 6. Three-dimensional distributions of the test chart.

clear all-focused image as shown in Fig. 6(a) can be obtained by the image filtering process. The small step of about 0.4 cm in the depth direction was successfully measured. The shape and depth information of the sample target can also be derived from our technique.

The acquisition times of this LC lens system without any mechanical movements must be faster than those of the conventional all-focused imaging system with mechanical movements such as a piezoelectric motor or stepping motor. The investigation of the interesting topic about the speed and accuracy of our system is now in progress.

5. Conclusion

The all-focused image and the depth mapping image of the sample target as the test chart can be determined by our proposed image digital filter from continuous focal images. The sharp and clear all-focused and depth mapping images can be obtained by the image filtering process. The acquisition times of this LC lens system without any mechanical movements must be faster than those of the conventional all-focused imaging system with mechanical movements such as a piezoelectric motor or stepping motor.

Funding

This work was partially supported by Grant-in-Aid for Scientific Research Young Scientists (B) from JSPS KAKENHI; Grant Numbers 90312694.

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