An optical image stabilization using a droplet manipulation on a liquid crystal and polymer composite film

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ABSTRACT

Motion blur is one of the major factors decreasing the image quality of a hand-held optical imaging system while the system is under shakes or vibrations during exposure. Optical image stabilization (OIS) is a technique to reduce such a blurring. The basic principle of OIS is to stabilize the recorded image in a camera by varying the optical path to the sensor under vibrations during exposure. In this paper, we demonstrate optical image stabilization (OIS) for an imaging system using a droplet manipulation on a liquid crystal and polymer composite film (LCPCF) that reduces the motion blur. The mechanism is based on manipulation of position of the liquid lens on LCPCF by means of electrically adjusting orientations of liquid crystals. The change of the position of the liquid lens compensates the deviation of light when the image system is under a handshake vibration. Therefore, the imaging system forms a clear image with a droplet on different position to overcome handshake vibration. The concept in this paper can also be extended to design other optical components for modulating the direction of light.

Keywords: Optical image stabilization, Liquid crystal

1. INTRODUCTION

One of the major factors for decreasing the image quality is the motion blur. Motion blur is caused by shakes or vibrations during the exposure of an optical imaging system [1]. It is a common problem in hand-held optical imaging system, such as camera. To reduce the degradation caused by motion blur, optical image stabilization (OIS) is adopted [2]. The concept of OIS is to stabilize the recorded image by varying the optical path to the sensor. This technique can be classified into two categories: one is to use a movable lens within an imaging system, and the other is to use a movable sensor. However, a mechanically movable device for OIS function increases the weight and total volume of the imaging system. Electrically controlled OIS systems with light and compact design have been proposed [3-4]. For correcting the

Liquid Crystals XIX, edited by Iam Choon Khoo, Proc. of SPIE Vol. 9565, 95651C

doi: 10.1117/12.2188871

motion blur, especially like pan-motion, liquid crystal (LC) lenses with multi-electrodes design have the function of axis-tunability [5-7]. Recently, our group developed a liquid crystal and polymer composited film (LCPCF) whose surface free energy can be electrically manipulated by external electrical field [8-14]. Due to the imbalance net Young's force induced by the non-uniform wettability, a droplet on the LCPCF moves when the inhomogeneous electrical field is applied on the LCPCF. The moving droplet on LCPCF can mimic a movable liquid lens to achieve OIS function. In this article, we demonstrate the feasibility of the concept, a droplet manipulation on a LCPCF for an OIS system.

2. OPERATING PRINCIPLE

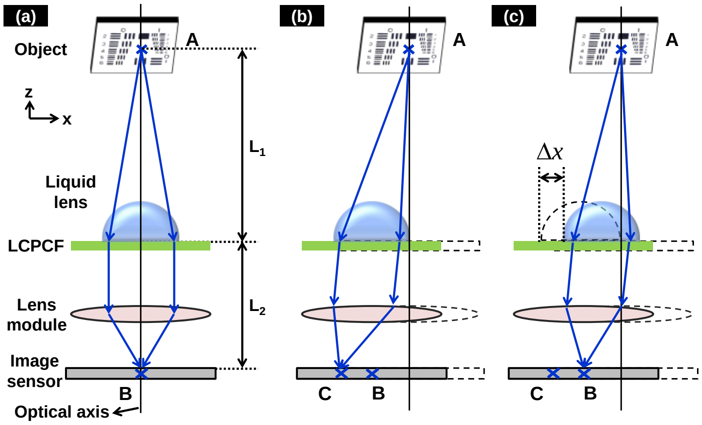

Fig. 1 Operating principles of the proposed OIS system. (a) The object (point A) is imaged onto the image sensor at point B by a liquid lens and lens module. (b) The optical imaging system under shacks during the exposure time, and the object (point A) is imaged onto image sensor at point C. (c) With a movable liquid lens, the object (point A) can be image back to point B.

The concept of the OIS image system based on the droplet manipulation on LCPCF is illustrated in Fig. 1(a)-1(c). The proposed OIS system consists of an image sensor, a lens module, and a droplet on LCPCF as a movable liquid lens. In Fig. 1(a), an object located at point A is imaged to sensor at point B through the droplet and lens module. The distance between the object and the liquid lens is L$_1$, and the distance between the liquid lens and image sensor is L$_2$. Then we adopt the frequency analysis of the system under incoherent illumination. Assume the spatial intensity distribution of the object is $f(x,y)$, and the impulse response of the imaging system is $h(x,y)$. Thus, the spatial intensity distribution of image $g(x,y)$ can be written as [15]:

$$g(x,y) = f(x,y) \otimes h(x,y), \tag{1}$$

where $\otimes$ stands for convolution operation. The impulse response $h(x,y)$ is combination of diffraction, aberrations, and other effects, such as motion blur. To discuss the performance of an imaging system, we can analyze the modulation transfer function (MTF) that comes from the Fourier transform of the impulse response. For an ideal case of the image formation, the MTF should be 1, meaning the impulse response is a delta function ($h(x,y) = \delta(x,y)$). For easy understanding, we assume the imaging system moves toward –x-direction in the integrated time of T_e, and then the image point B moves to the point C, as shown in Fig. 1(b). Next, we can isolate the effect of motion blur from impulse response. Impulse response of one-dimensional motion in an imaging system can be expressed as:

$$h_{motion}(x)=\int_0^{T_e}\delta(x-(\frac{L_2}{L_1}\times\upsilon_{sys}\times t))dt\,, \tag{2}$$

where the υ_{sys} stands for the velocity of the imaging system. The Fourier transform of Eq. (2) is MTF_{motion} :

$$MTF_{motion}(\xi)=\left|\sin c(\xi\times\frac{L_2}{L_1}\times\upsilon_{sys}\times T_e)\right|, \tag{3}$$

where ξ is the spatial frequency corresponding to spatial x-domain. From Eq. (3), the larger the velocity υ_{sys} is, the worse the image performance is. For achieving the function of OIS, we need to move the liquid lens toward +x direction to prevent the reduction of MTF_{motion} , as shown in Fig 1(c). In the period of integrated time, the liquid lens moves a distance of Δx with a velocity of V_{liquid} ($\Delta x=\upsilon_{liquid}\times T_e$), and then the object is imaged onto the point B due to the variation of optical path. Based on the geometrical relationship between the object, movable lens, and image sensor, the velocity of the liquid lens toward +x direction should be:

$$\upsilon_{liquid}=\upsilon_{sys}\times\left(\frac{L_2}{L_1+L_2}\right). \tag{4}$$

Thus, the Eq. (3) for a movable liquid lens can be rewritten as:

$$MTF_{motion}(\xi)=\left|\sin c(\xi\times(\frac{L_2}{L_1}\cdot\upsilon_{sys}-\frac{L_1+L_2}{L_2}\cdot\upsilon_{liquid})\times T_e)\right|. \tag{5}$$

Base on Eq. (4) and Eq. (5), when the velocity of liquid lens closes to the requirement, the motion blur can be reduced by operating a liquid lens as an OIS function.

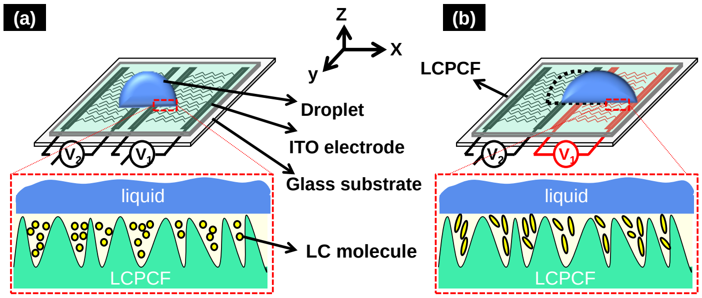

Fig. 2 Operating principles of a droplet as a movable lens on LCPCF. (a) Without applied voltage on LCPCF, the LC molecules directly aligned along y-direction. (b) When a voltage is applied on the right region ($V_1 > V_2 = 0$), the LC molecules on the right region tilt up and the droplet moves to right region.

To manipulate the liquid lens on LCPCF, the LCPCF are fabricated on patterned indium tin oxide (ITO) electrodes on the glass substrate, as shown in Fig. 2(a). The ITO electrodes are zigzag-patterned. In Fig. 2(b), the droplet is placed between two identical groups of zigzag ITO electrode regions. The voltage applied on the right and left ITO electrode regions are denoted as V_1 and V_2, respectively. When the voltage is applied to the right region rather than the left region ($V_1>V_2=0$), the LC molecules on the right region tilt up. As a result, the right region of LCPCF is more hydrophilic than the left region. The droplet on LCPCF experiencing an imbalance net Young's force moves toward right-direction (+x-direction). On the other hand, when the voltage is applied on the left region rather than the right region ($V_2>V_1=0$), the droplet moves toward left-direction (-x-direction). Thus, we can manipulate the droplet movement by controlling the orientations of the LC molecules at different region on LCPCF.

3. EXPERIMENTAL RESULTS AND DISCUSSION

To demonstrate the feasibility of the proposed OIS system, we prepared a liquid lens on LCPCF. The fabrication detail of LCPCF is described in literature [14]. We filled the mixture of nematic LC (Merck, E7), reactive mesogen (Merck, RM257), and photoinitiator (Merck, IRG-184) at a ratio of 69:30:1 wt% into the gap between two glass substrates. One of the substrates was coated with mechanically buffered polyimide (PI), and the other one was the zigzag-patterned ITO substrate without PI. The corner angle of the zigzag ITO strips is 150 degrees. The width of an electrode stripe and the spacing between adjacent electrode strips are 4 μm and 14 μm, respectively. After the filling process, we exposed the sample to UV light of 10 mW/cm^2 at 68^0 Celsius for 50 minutes. After the phase separation and photo-polymerization, the substrate with PI was peeled off and the LCPCF was left on the zig-zag-ITO electrode. The thickness of the fabricated LCPCF is around 10 μm.

To test the movement of water droplet on LCPCF, we placed a water droplet of 6ml on LCPCF and recorded the dynamics of the droplet at different applied voltage of V_1 (Fig. 2) with a CCD (JAI CVM30, frame rate: 120 frames/sec). The moving distance as a function of time at different V_1 is shown in Fig. 3(a). The moving distance increases with time. The moving distance is longer when the voltage is larger. We converted Fig. 3(a) to the voltage-dependent velocity (υ_{liquid}) in Fig. 3(b). υ_{liquid} is a velocity defined as droplet distance between 60ms and 150ms. In Fig. 3(b), the largest υ_{liquid} is 2.8mm/s at V_1=200V $_{rms}$. The droplet is hardly moved when V_1<60V $_{rms}$. This is because the wettability difference is not large enough to drive the droplet when the V_1 is too small.

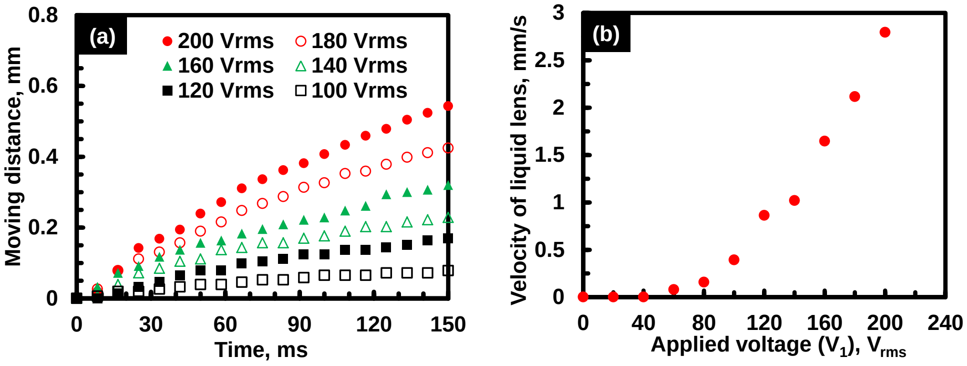

Fig. 3 (a) The moving distance of water drop of 6 μl as a function of time under different applied voltage (i.e. V_1 in Fig.2) (b) The velocity of the water droplet as a function of V_1.

To test OIS system in Fig. 1, we placed a droplet on LCPCF and set V_1=0. A resolution chart (USAF 1591) was used as an object and a webcam (Pro 9000) was used to record the image. The setting of the system is: L_1=5mm, L_2=3.9mm, and T_e= 60ms. The LCPCF sample was placed on a motorized translation stage. Without applied voltage on LCPCF, we moved the translation stage at different speed to simulate the imaging system under vibrations. The images were shown in Fig. 4(a). When the speed of the translation stage is faster, the image is more blurred which indicates motion blur is severer. We then converted the image in Fig. 4(a) to modulation transfer function (MTF) as a function of spatial frequency in Fig. 4(b). The MTF drops with the spatial frequency. In Fig. 4(b), the cutoff frequency is around 75 lp/mm without vibration. The cutoff frequency drops to 44 lp/mm, 33 lp/mm, and 18 lp/mm as υ_{sys} is 1.2mm/s, 3.6mm/s, and 6.0mm/s, respectively. This also indicates the vibration of imaging system affect the image quality and cause motion blur. The translation speed is faster, the cutoff frequency is lower.

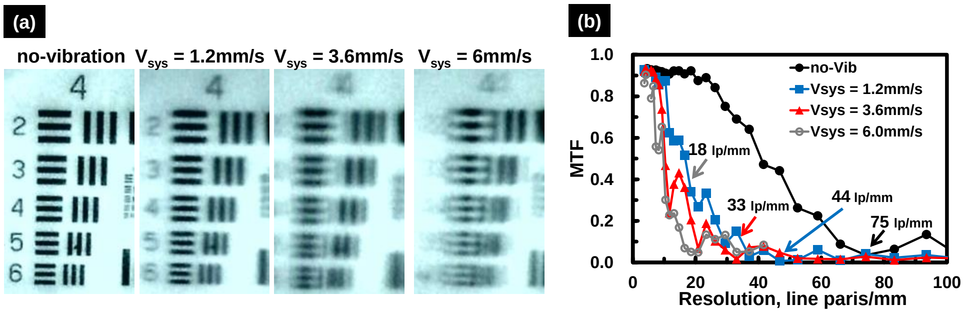

Fig. 4 (a)The captured images when the translation stage moves at different speed and the droplet is static.(i.e. $\upsilon_{sys} \neq 0$, υ_{liquid} =0). (b) MTF as a function of resolution (spatial frequency).

To demonstrate the imaging stabilization using proposed system, we moved both of the translation stage and the droplet on LCPCF in the opposite direction. The speeds of translation stage and the droplet on LCPCF are υ_{sys} =3.6mm/s and υ_{liquid} =1.64mm/s (V_1=160V_{rms}) for OIS-on , respectively. The images are shown in Fig. 5(a). In Fig. 5(a), the left image shows the motion blur when OIS is off (υ_{liquid} =0) and the translation stage is at υ_{sys} =3.6mm/s. The right image shows the image stabilization when OIS is on (υ_{liquid} =1.64mm/s) and the translation stage is still at υ_{sys} =3.6mm/s. Compared to the right image for the static condition (no vibration, υ_{sys} =0) and the left image for the OIS-off, the OIS system can improve the image of the motion blur, but still need has room to further image quality. The MTF as a function of spatial frequency is also plotted in Fig. 5(b). The cutoff frequency increases from 33 lp/mm to 52lp/mm as OIS turns on. To further improve image quality, the curvature of the droplet and the speed of the droplet should be carefully optimized.

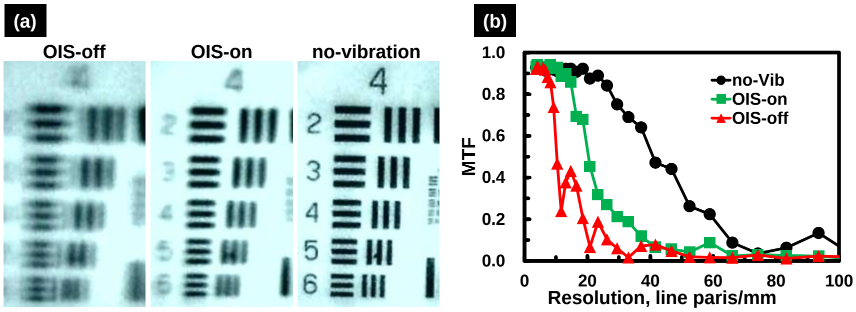

Fig. 5 (a)The image for the OIS is off(left, υ_{liquid} =0),and OIS is on(middle, υ_{liquid} =1.64mm/s) when the translation stage moves at a speed of υ_{sys} =3.6mm/s . The left one is the image with no vibration (υ_{sys} =0). V_1=160V_{rms} for the condition of OIS-on. (b) MTF as a function of resolution (spatial frequency).

4. CONCLUSION

In this article, the feasibility of an electrically droplet manipulated OIS system on LCPCF is demonstrated. The image blur can be reduced by manipulating the position of the droplet on LCPCF on a basis of an inhomogeneous surface free energy distribution. The proposed OIS system is capable of compensating a shaking or a vibration on imaging system while the velocity of imaging system is less than 4.8mm/s.

ACKNOWLEDGEMENTS

The authors are indebted with Po-Ju Chen, Jing-Yi Wang, and Chun-Yu Hsu for technical assistance. The translation stage was lent by Prof. Hao-Chung Kuo. This research was supported partially by Department of Natural Sciences and Sustainable Development in Ministry of Science and Technology (MOST) in Taiwan under the Contract No. MOST 104-2112-M-009 -010 -MY3 and partially by Liqxtal Technology Inc.

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