An electrically tunable imaging system with separable focus and zoom functions using composite liquid crystal lenses

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Abstract: We demonstrated an electrically tunable optical image system with separable focus function and zoom function based on three tunable focusing composite liquid crystal (LC) lenses. One LC lens in charge of the focus function helps to maintain the formed image at the same position and the other two LC lenses in charge of zoom function assist to continuously form an image at image sensor with tunable magnification of image size. The detail optical mechanism is investigated and the concept is demonstrated experimentally. The magnifications of the images can be switched continuously for the target in a range between 10 cm and 100 cm. The optical zoom ratio of this system maintains a constant~6.5:1 independent of the object distance. This study provides not only a guideline to design the image system with an electrically optical zoom, but also provide an experimental process to show how to operate the tunable focusing lenses in such an image system.

OCIS codes: (230.3720) Liquid-crystal devices; (230.2090) Electro-optical devices.

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1. Introduction

An imaging system with electrically tunable focus and zoom functions is important in cell phones, pico projectors, holographic projection systems, and endoscopes [1–8]. Conventionally, optical zoom system consists of many lenses and a voice coil motor(VCM) to control the relative distance of lenses. The lenses are categorized as two groups: one is focusing group for focus function which means the image is adjusted in focus or out of focus. The other is zooming group for zoom function which means the adjustment of the magnification of the image. By manually changing the relative positions of solid lenses, the focus function and zoom function could be performed separately. However, the optical zoom systems within mechanical moving parts are too bulky for portable devices. To remove mechanical moving parts, many active-optical elements can be used for realizing electrically tunable optical zoom systems, such as liquid lenses [1,9–11], deformable mirrors [1,12], and liquid crystal (LC) lenses [1–8,13–15]. The focal lengths of the LC lenses are electrically tunable owing to the spatial distribution of the refractive indices resulting from the orientations of LC molecules. The features of LC lenses are light weight, low power consumption, and the capability of a transmissive mode. Many structures of LC lenses are developed for focus functions of portable imaging systems [1,2,16–19]. The optical zoom system with an electrically tunable optical zoom ratio was first studied theoretically in 1992 [13]. In 2011, we experimentally realized an electrically tunable optical zoom system using two LC lenses for the object distance in a range from 10 cm to infinity and the maximum optical zoom ratio was 5.6:1 [4]. However, the optical zoom ratio of such a system decreases as the object distance increases because the focus function and the zoom function are not separable which results from one of LC lenses in charge of both of focus and zoom functions. Many applications related to photography actually require an optical zoom system with separable focus and zoom functions. In this paper, we demonstrated an electrically tunable imaging system with separable focus function and zoom function based on three composite LC lenses. One LC lens is in charge of the focus function of the object by means of electrically adjusting the focal length in order to maintain the formed image at the same position. Such a formed image at the same position then continuously forms an image at the image sensor by the other two LC lenses which perform the function of zoom in and zoom out using electrically changing the focal lengths of the other two LC lenses. The optical mechanism is discussed and the experiments are performed to demonstrate the concept. The magnifications of the images can be switched continuously and the optical zoom ratio of this system maintains a constant~6.5:1 independent of the object distances. This study can provide

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researchers and engineers a guideline to design the portable devices with an electrically optical zoom.

2. Operating principle and sample preparations

The structure of the designed optical zoom system consists of a focusing group, a zooming group and a camera system, as depicted in Fig. 1. The focusing group is made up of a target (or an object), a polarizer and an LC focusing lens. The zooming group consists of an LC objective lens and an LC eyepiece lens. The focal lengths of the LC focusing lens, the LC objective lens, and the LC eyepiece lens are f_f, f_o, and f_e, respectively. The optical powers of three LC lenses, defined as the reciprocal of the focal lengths, denote $\phi_f = 1/f_f$, $\phi_o = 1/f_o$, and $\phi_e = 1/f_e$, respectively. The distance between the target and the LC focusing lens is p. The distance between the LC objective lens and the LC eyepiece lens is d. Because the LC focusing lens is attached to the LC objective lens, the distance between those two LC lenses can be neglected when the distance is much smaller than p and d. The incident light can be collected into the image sensor of the camera when lens powers of three LC lenses are zero.

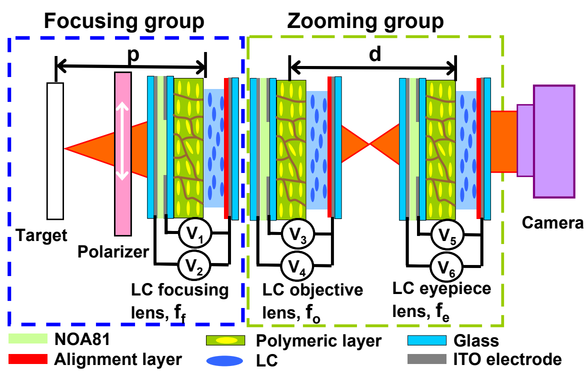

Fig. 1. The structure of the electrically tunable optical zoom system using three composite LC lenses. A white arrow of the polarizer indicates the transmissive axis of the polarizer. f_f, f_o, and f_e stand for the focal lengths of the LC focusing lens, the LC objective lens, and the LC eyepiece lens respectively. V_1, V_2, V_3, V_4, V_5, and V_6 are applied voltages of three LC lenses.

To prove that the zoom function and focus function of the proposed system in Fig. 1 are separable, the following discussions are based on the image formation of first-order optics. We begin our derivation by not enforcing independence of the focus and zoom functions for the purposes of optimizing the performance of a system with the choice of the lens powers that will be chosen later to allow the independence of focus and zoom. Assume that the image distance after light passes through the LC focusing lens is “a”. The image distance after light passes through the LC objective lens is “b” when the object distance of the LC objective lens is “a”. The image system in Fig. 1 should satisfy the following three sub-equations according to the thin-lens equation [20]:

$$\begin{cases} \dfrac{1}{p} - \dfrac{1}{a} = \phi_f \\ \dfrac{1}{a} - \dfrac{1}{b} = \phi_o \\ \dfrac{1}{d+b} - \dfrac{1}{\infty} = \phi_e \end{cases}, \tag{1}$$

Equation (1) follows sign conventions of first-order optics. Typically, the image on image sensor is inverted and is converted to an erect image by an image process. The angular magnification of the image (M) is: $b/(b+d)$ [20]. The image is erect as M>0 and inverted as M<0. The image is magnified when |M|>1 and minified when |M|<1. According to Eq. (1) and expression of M, M as a function of ϕ_f and ϕ_o can be expressed in Eq. (2).

$$M(\phi_f,\phi_o)=\frac{p}{p-p\times d\times(\phi_f+\phi_o)+\mathrm{d}}. \tag{2}$$

Similarly, M as a function of ϕ_e can be written as Eq. (3).

$$M(\phi_e)=1-\phi_e\times d. \tag{3}$$

In order to keep M = 1 and from Eq. (2) and Eq. (3), two extra-conditions need to be followed: $\phi_f+\phi_o=\dfrac{1}{p}$ and $\phi_e=0$. The image is zoomed in when |M|>1 and zoomed out when |M|<1.

Next, the constraints of the LC lenses are considered to obtain the optical zoom ratio of the system. We assume that three LC lenses are identical and each of them could be operated as a positive lens or a negative lens. The lens powers of three LC lenses (ϕ_{LClens}) are assumed in a range: $\phi_{\min}\le\phi_{LClens}\le\phi_{\max}$, where $\phi_{\min}<0$, $\phi_{\max}>0$, and $|\phi_{\min}|<|\phi_{\max}|$. When M is positive (i.e., M>0), the minimum of M (i.e., M_{min}) occurs at $\phi_f=\phi_o=\phi_{\min}$ and then M_{min} is expressed in Eq. (4).

$$M_{\min}=\frac{1}{1-2\times d\times\phi_{\min}+d/p}. \tag{4}$$

Similarly, the maximum of M (i.e., M_{max}) occurs at $\phi_e=\phi_{\min}$ and then M_{max} is expressed in Eq. (5).

$$M_{\max}=1-d\times\phi_{\min}. \tag{5}$$

Optical zoom ratio (ZR) is defined as the ratio of M_{max} to M_{min} (i.e., ZR = M_{max}/M_{min}). From Eq. (4) and Eq. (5), ZR of the system can be written in Eq. (6).

$$ZR=(1-2\times\mathrm{d}\times\phi_{\min}+\frac{d}{p})\times(1-d\times\phi_{\min}). \tag{6}$$

When p changes in Eq. (1), the lens powers of three LC lenses change in order to keep the image in focus which also means the focus function of the system. From Eq. (2) and Eq. (6), ZR increases as p decreases and M also changes with p. This means the zoom function of the system depends on the object distance of the target. In addition, the focus function and zoom function are not separable. However, our goal is to design a zoom system with independent focus and zoom functions; meanwhile, maintaining a constant optical zoom ratio independent of p. To achieve the goal, we have to specially choose "a" in Eq. (1) and keep "a" as an invariable. In the first sub-equation of Eq. (1), d/p is equal to $d\times\phi_{\min}+d/a$ when $\phi_f=\phi_{\min}$. As a result, ZR in Eq. (6) then can be expressed as:

$$ZR=(1-2\times\mathrm{d}\times\phi_{\min}+\frac{d}{a})\times(1-d\times\phi_{\min}), \tag{7}$$

which is independent of p. Therefore, ZR in Eq. (7) is a constant by adjusting lens powers of three LC lenses in order to keep a constant "a". From the first sub-equation of Eq. (1) and the range of the LC lenses, the range of p is: $\frac{a}{a\times\phi_{\max}+1}\le p\le\frac{a}{a\times\phi_{\min}+1}$. As a result, "a" should be larger than $-1/\phi_{\min}$ (i.e., $a\ge-1/\phi_{\min}$) when the farthest target is located at the infinity (i.e., $p\le\infty$). Furthermore, the value of "a" can also affect the value of optical zoom ratio of the system and the working range of the object distance. Therefore, proper designing the image distance after light passes through the LC focusing lens ("a") by adjusting lens powers of three LC lenses can realize an image system with an electrically tunable zoom function while maintaining a constant optical zoom ratio within separable zoom function and focus function.

3. Experiment and discussion

In order to demonstrate the concept we proposed, we used three composite LC lenses, as depicted in Fig. 1. The fabrication process of three composite LC lenses is reported in previous literature [4]. Each composite LC lens consisted of three indium-tin oxide (ITO) glass substrates with a thickness of 0.7 mm, an isolating layer (NOA 81, Norland Optical Adhesive) with a thickness of 35 µm, mechanically buffered alignment layers (Polyvinylalcohol or PVA), a polymeric layer with thickness of 35 µm, and an LC layer (MLC-2144, Merck, Δn = 0.2493 for λ = 589.3 nm at 20°C) with a thickness of 50 µm. The ITO layer in the middle of the glass substrate was etched with a hole-pattern within a diameter of 1 mm. The material of polymeric layer was made of nematic LC, (MLC-2144, Merck, Δn = 0.2493 for λ = 589.3 nm at 20°C), reactive mesogen (RM 257, Merck), and photoinitiator (IRG-184, Merck) at 30: 69: 1 wt% ratios. The polymeric layer has a fixed lens power ~-2.5 m^{-1} because of the lens-like distribution of refractive indices generated by the voltage-curing process. The LC directors in the LC layer aligned by the polymeric layer and PVA were aligned homogeneously with a pretilt angle ~2 degree [4,17,18,21]. Each composite LC lens was operated by two voltages,(for example:V1 and V2 in Fig. 1 for LC focusing lens). The lens power of the composite LC lens is the combination of the lens power of the polymeric layer ϕ_p and the LC layer $\phi_{LC}(V_1,V_2)$ which can be expressed as $\phi_{LClens}(V_1,V_2)=\phi_p+\phi_{LC}(V_1,V_2)$. When $V_1>V_2$, the LC layer acts as a positive lens because the tilt angles of LC directors of the LC layers in the center of the hole-electrode are smaller than those near the edge of the hole-electrode. Conversely, when $V_2>V_1$, the LC layer acts as a negative lens. The negative lens power of the polymeric layer can shift the negative lens power.

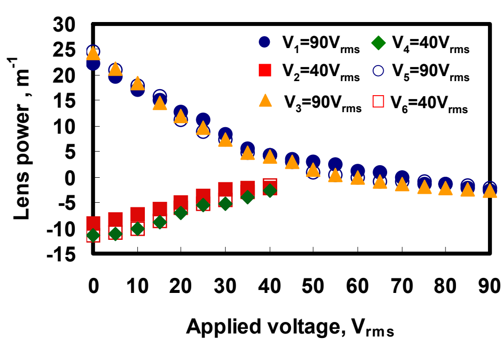

Fig. 2. The lens power as a function of applied voltages for LC focusing lens, LC objective lens and LC eyepiece lens. λ = 532 nm.

To measure the lens powers of three composite LC lenses, we observed concentric rings of the phase profiles of three composite LC lenses at different voltages under crossed polarizers. We then converted the phase profiles to the lens powers [4]. The lens power as a

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function of applied voltages is shown in Fig. 2. In Fig. 2, the lens power of the LC focusing lens was zero at $V_1 = 90\ V_{rms}$ and at $V_2 = 70\ V_{rms}$ because no fringe was observed. This also indicates the lens power of the LC layer of the LC focusing lens was equal to the minus lens power of polymeric layer which was 2.5 m^{-1}. When 90 V_{rms}>V_2 > 70 V_{rms} at $V_1 = 90\ V_{rms}$, the lens power of the LC focusing lens was switchable from −2.5 m^{-1} to 0 m^{-1}. When 70 V_{rms}>V_2 > 0 V_{rms} at $V_1 = 90\ V_{rms}$, the lens power was switchable from 0 m^{-1} to 22.1 m^{-1}. When 40 V_{rms} > V_2 > 0 V_{rms} at $V_2 = 40\ V_{rms}$, the tunable lens power was from −2.5 m^{-1} to −9.2 m^{-1}. Therefore, the tunable lens power of the LC focusing lens was from −9.2 m^{-1} to 22.1 m^{-1}. Similarly, the tunable range was from −11.3 m^{-1} to 24.3 m^{-1} for LC objective lens and was from −11.3 m^{-1} to 24.9 m^{-1} for LC eyepiece lens. From Fig. 2, the lens powers of three composite LC lenses are similar.

To choose a proper image distance after light passes through the LC focusing lens (i.e. "a"), we measured the maximum object distance as a function of "a". "d" in Fig. 1 was set as 10 cm. The experimental procedure is as follows. We first applied voltages to the LC focusing lens and the LC eyepiece lens at (V_1,V_2) = (90 V_{rms}, 70 V_{rms}) and (V_5,V_6) = (90 V_{rms}, 55 V_{rms}) for $\phi_f = \phi_e = 0$. The object was many black squares. Then we changed the applied voltages of the LC objective lens till we obtained the sharpest or clear image of the target. The applied voltages (V_3,V_4) of the LC objective lens were (90 V_{rms},27 V_{rms}), (90 V_{rms},26 V_{rms}), (90 V_{rms}, 25.5 V_{rms}), (90 V_{rms}, 19.5 V_{rms}), and (90 V_{rms}, 16 V_{rms}) for obtaining the images in focus as the target located at 13 cm, 12 cm, 11 cm, 10 cm, and 9 cm, respectively. Since "a" is the object distance of the LC objective lens or the image distance of the LC focusing lens, this also means we obtained the voltage pairs (V_3,V_4) of the LC objective lens for the corresponding "a" of 13 cm, 12 cm, 11 cm, 10 cm, and 9 cm. For calibration of the magnification, the sizes of the clear images we obtained at different "a" is our standard image size for M = 1 at different "a". After we fixed "a" while kept $\phi_e = 0$, we adjusted the position of the target and also adjusted lens power of the LC focusing lens by applying different (V_1,V_2). Then we recorded the largest distance of the target away from the LC focusing lens at which we can see the target clearly. Such a largest distance was the maximum object distance (p_{max}) for a fixed value of "a". We then repeated the process for different "a". Due to the limitation of the depth-of-field of the camera system, we recorded p_{max} as 100 cm when the object distance was larger than 100 cm. p_{max} as a function of "a" is plotted in Fig. 3. In Fig. 3, p_{max} increases with "a" when "a"<11 cm. When "a">11 cm, p_{max} remains 100 cm. In order to obtain the maximum optical zoom ratio (ZR) of the image system and large range of the object distance, we choose "a" of 11 cm for the following experiments. The function of Fig. 3 is to help us to find out the proper "a" in order to achieve large ZR in a proper range of the object distance. For example, we can choose "a" of 10 cm if the range of the object distance of the system is 50 cm.

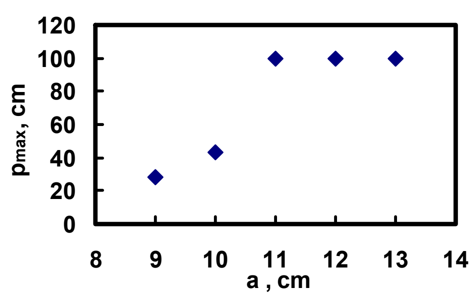

Fig. 3. Maximum object distance (p_{max}) of the system as a function of a. d = 10 cm. The light source was white light.

To test the focus function of the LC focusing lens, we measured the object distance as a function of the lens power of the LC focusing lens (ϕ_f) while keeping "a" = 11 cm and $\phi_e = 0$.

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The magnification of the image size was unchanged. The target was located at different locations and then we adjusted the lens power of the LC focusing lens by adjusting (V_1,V_2). The recorded voltage pairs (V_1,V_2) for clear images were (90 V_{rms}, 65 V_{rms}), (27 V_{rms}, 40 V_{rms}), (19 V_{rms}, 40 V_{rms}), (17 V_{rms}, 40 V_{rms}) and (0 V_{rms}, 40 V_{rms}) for p of 10 cm, 20 cm, 30 cm, 50 cm, and 100 cm, respectively. By comparing Fig. 2 and the recorded voltage pairs (V_1,V_2), the corresponding lens powers of the LC focusing lens were obtained. The experimental results are shown in Fig. 4. The object distance decreases with the lens power of the LC focusing lens. In addition, the lens power of the focusing lens is zero for object distance of 11 cm which is "a" = 11 cm. When the object distance is larger than 11 cm, the image is blurred and it requires a negative lens power of the LC focusing lens in order to see the image clearly. Similarly, the lens power of the LC focusing lens is positive when the object distance is closer less than 11 cm [16,19]. We also plotted the calculated results in Fig. 4 based on the first sub-equation of Eq. (1). The discrepancy between experiments and calculations mainly results from the depth-of-field of the camera system. In fact, the magnifications of the images in Fig. 4 do not change. This indicates that the LC focusing lens can perform the focus function only without changing the magnification of the image.

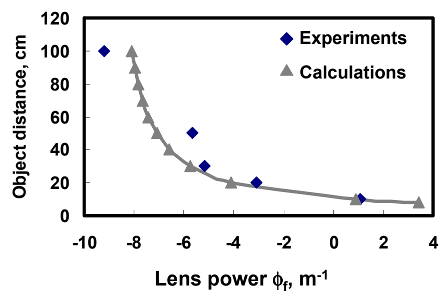

Fig. 4. The object distance of the system as a function of lens power ϕ_f. d = 10 cm and "a" = 11 cm. The light source was white light. (V_3,V_4) = (90 V_{rms}, 25.5 V_{rms}) and (V_5,V_6) = (90 V_{rms}, 55 V_{rms})

Next, we tested the zoom function of the image system. To perform the zoom function using the zooming group only in Fig. 1, we have to keep "a" unchanged (i.e. 11 cm here) by using the focus function of the LC focusing lens. The image size changes when the lens powers of the lenses of the zooming group changes at a fixed object distance of the zooming group. The target was placed at 20 cm (i.e. p = 20 cm) and lens power of the LC focusing lens was set as −3.11 m^{-1} (i.e. (V_1,V_2) = (27 V_{rms}, 40 V_{rms})) according to Fig. 4. We recorded the images by adjusted the lens powers of the LC objective lens (ϕ_o) and the LC eyepiece lens (ϕ_e) (i.e. change (V_3,V_4) and (V_5,V_6)). The magnification of the image was obtained by comparing the change of the image size. The magnification as a function of ϕ_o and ϕ_e is plotted is Fig. 5(a). From Fig. 5(a), the magnification indeed can be adjusted by manipulating the lens powers of the LC objective lens and the LC eyepiece lens. The calculated result (gray line with triangles) based on Eq. (2) and Eq. (3) is also plotted in Fig. 5(a). The results are quite similar. From Fig. 5(a), we plotted Figs. 5(b) and 5(c). We repeated the similar process as p changes and the results are also plotted in Figs. 5(b) and 5(c). From Figs. 5(b) and 5(c), the magnification increases when ϕ_o increases and ϕ_e decreases. This means the image size can be magnified by changing the lens powers of two LC lenses in the zooming group. In addition, the magnifications v.s. ϕ_o and ϕ_e are similar when the object distance is changed. This also indicates that the zoom function and the focus function are separable by a fixed "a". Moreover, the zoom function and the focus function are electrically tunable. From Figs. 5(b) and 5(c), we obtained M_{max}, M_{min}, and ZR as a function of the object distance (p), as shown in Fig. 6. The calculated results are also plotted according to Eqs. (4), (5), and (7). In Fig. 6, M_{max} remains ~2.2, M_{min} remains ~0.3 and ZR remains similar around 6.5:1. As a result, we can realize an electrically tunable optical zoom system using three composite liquid crystal lenses with independent focus and zoom functions. The optical zoom ratio is independent of the object distance.

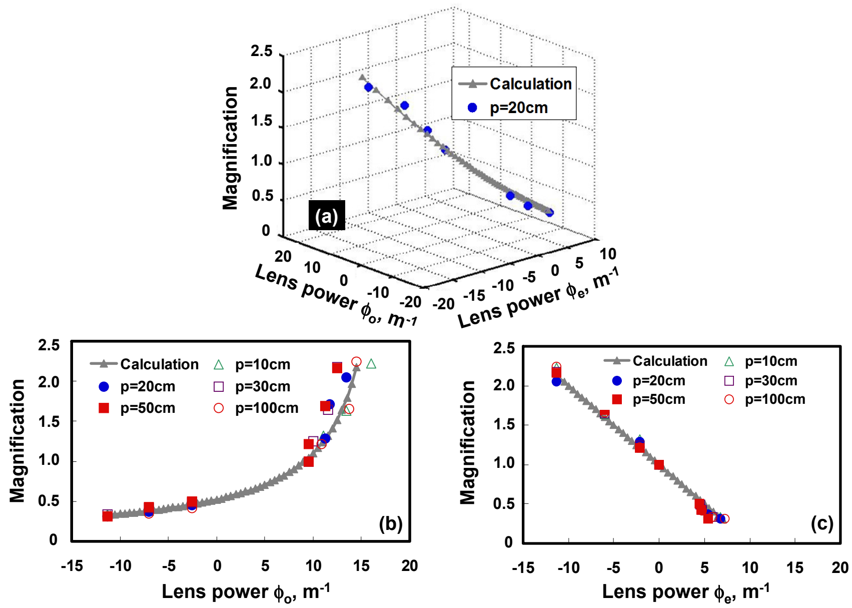

Fig. 5. Magnification as a function of lens power of (a) the LC objective lens and the LC eyepiece lens when p = 20 cm. (b) and (c) are sliced from (a). (b) Magnification as a function of the LC objective lens at different p. (c) Magnification as a function of the LC eyepiece lens at different p. Gray line with gray triangles indicate the calculation results. d = 10 cm. a = 11 cm.

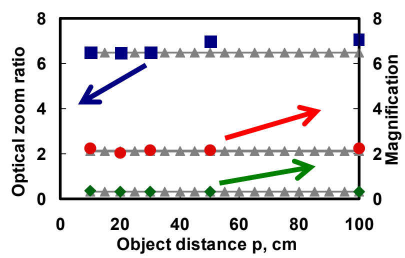

Fig. 6. Optical zoom ratio, maximum magnification and minimum magnification as a function of the object distance p. Blue squares are the experimental results of optical zoom ratio. Red circles are the experimental results of maximum magnification. Green diamonds are the experimental results of minimum magnification. Gray triangles are the calculated results. d = 10 cm and a = 11 cm.

Figures 7(a)–7(c) show the image performance at different magnifications when p = 20 cm and $\phi_f = -3.11\ m^{-1}$. The photos were taken under ambient white light. The magnification of Fig. 7(b) is one. Similarly, the image performances at different object distance are also shown in Figs. 7(d)–7(i). The optical zoom ratios at different object distance are around 6.5:1. The image can be magnified and reduced by adjusting the lens powers of the LC objective lens and the LC eyepiece lens. The image quality is not good because of dispersion of LC materials, 2) vignetting resulting from small apertures, and 3) imperfect phase profiles [20]. Using LC with lower dispersion, enlarging aperture size of LC lenses, and improving the phase profiles of LC lenses can improve the image quality. To improved the ZR, the tunable range of lens powers of the LC lenses should be enlarged [1,2,19]. Moreover, the polarizer of the LC lenses decreases light efficiency ~50%. In order to increase the light efficiency, polarizer-free LC lenses based on polarization independent LC phase modulators are required [19,22–28].

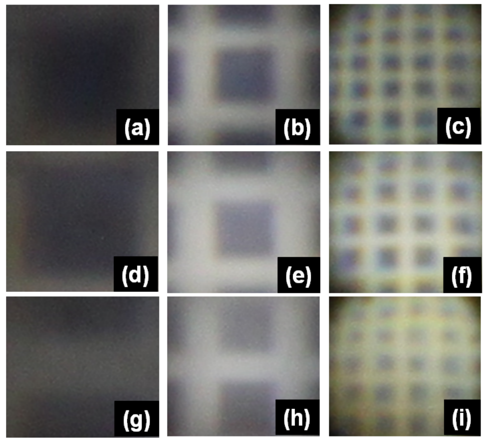

Fig. 7. Image performance of the zooming system when the target is at p of 20 cm and $\phi_f = -3.11\ m^{-1}$. (a) Magnification (M) = 2.05 (b) M = 1 (c) M = 0.32; when the target is at p of 50 cm and $\phi_f = -5.66\ m^{-1}$. (d) M = 2.17 (e) M = 1 (f) M = 0.31; when the target is at p of 100 cm and $\phi_f = -9.2\ m^{-1}$. (g) M = 2.24 (h) M = 1 (i) M = 0.33.

4. Conclusion

We demonstrated an electrically tunable optical zoom system with separable focus function and zoom function based on three tunable focusing LC lenses. The mechanism we proposed can also be applied to other active lenses, such as electrowetting activated lens and another structures of LC lenses [2, 14]. We can estimate the optical zoom ratio of an imaging system is around 3:1 by using three electrowetting activated lenses (Varioptic, Arctic 316 or Arctic 39N0) whose minimum lens powers are $-5\ m^{-1}$. The optical room ratio is small and the power consumption is large (> 1 mW) in spite of the fast response time (< 500 ms). As to LC lenses without a polymeric layer, the minimum lens power of the LC lens is around $-8.7\ m^{-1}$ in general and the calculated optical room ratio is ~5.12:1, still smaller than our design (6.5:1) [2, 14]. This study provides not only a guideline to design the image system with an electrically optical zoom, but also provides an experimental process to show how to operate the LC lenses in such a system.

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