An electrically tunable optical zoom system with separated focusing and zooming functions

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ABSTRACT

In this paper, we demonstrated an electrically tunable optical zoom system with separated focusing and zooming functions. The optical mechanism is discussed. The focusing distance and magnification of the image can be controlled separately by focusing lenses and zooming lenses. As a result, the zoom ratio is independent of objective distance and only depends on the tunable range of the lens power of the active-optical elements. This study helps designing many applications with an optical zoom function, such as cell phones, holographic projectors, pico projectors and endoscopes.

Keywords: Liquid crystal lens; Electrically tunable zoom lens; Focusing function; Zooming function

1. INTRODUCTION

An electrically tunable optical focusing and zooming system is important in many applications, such as cell phones, pico projectors, holographic projection systems, and endoscopes.[1-5] For a conventional optical zoom system, the focusing function and zooming function are controlled by the mechanical movement of the solid lenses. Usually, two groups of the solid lenses in the zoom system: one group is in charge of focusing function and the other is in charge of zooming function. By controlling the relative distance of the solid lenses in the groups, we can adjust the objective distance which is clearly imaged to the image sensor and also the magnification of the images. However, the optical zoom system with the mechanical movement of the solid lenses is too bulky for portable devices. By adopting the active-optical elements, we can realize the electrically tunable-focusing optical zoom system. The active-optical elements can be liquid lenses[6-7], deformable mirrors[8] and liquid crystal (LC) lenses.[9-12] The first theoretical analysis of electrically tunable zoom system using LC elements was proposed in 1992.[12] Based on the theory, several optical system using two LC lenses are realized, but the objective distance of those systems is fixed, not tunable.[13-14] In 2011, we experimentally realized an electrically tunable-focusing optical zoom system using two composite LC lenses.[15] The zoom ratio of the optical zooming system reaches ~ 7.9:1 and the object can be zoomed in or zoomed out continuously at the objective distance of infinity to 10 cm. However, the focusing function and zooming function of such a system can not be separated. In this paper, we discussed theoretically an electrically tunable optical system with separated focusing function and zooming function based on three active-optical elements. Many factors are discussed, such as the tunable range of the lens power of active elements, the

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relative position of active elements, the magnifications, the focusing distance of the object and the zoom ratio of the system. By comparing the properties of the active optical elements, we can properly choose the type of active optical elements to realize the system. This study can help us to design an electrically tunable optical zooming system with separated focusing and zooming function for the portable devices.

2. OPERATING MECHANISM

To separate the focusing function and zooming function, the designed electrically tunable optical zoom system consists of a focusing group, a zooming group and a camera, as shown in Fig. 1. The focusing group consists of a target (or an object), and a focusing lens. The zooming group is made up of an objective lens and an eyepiece lens. Among the components, the focusing lens, the objective lens and the eyepiece lens are active-optical elements whose focal lengths are electrically tunable. The lens powers of the focusing lens, the objective lens, and the eyepiece lens are ϕ_f, ϕ_o, and ϕ_e, respectively. The objective distance between the target and the focusing lens is p. The distance between objective lens and eyepiece lens (or the length of the zooming group) is d. The focusing lens and objective lens are attached to each other and then the distance between those two lenses is around zero. Without three active-optical elements, the camera was set that the target is imaged to the image sensor of the camera when the target is at infinity (>1km).

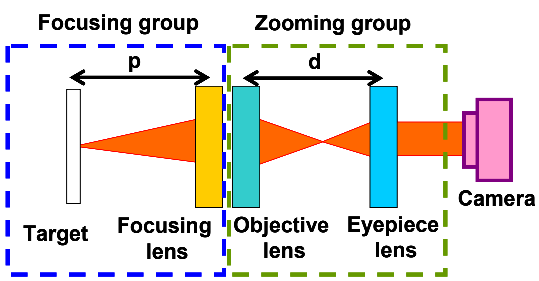

Fig. 1 The structure of the electrically tunable-focusing optical zoom system using three active-optical elements.

Next, we prove the optical mechanism of the zoom system in Fig. 1. The following optical discussions are based on approximation of thin lenses and the first-order optical design. When the incident light passes through three active-optical elements, the lens power of the focusing lens is electrically adjusted in order to maintain the position of the formed image. We define the distance between the formed image and the focusing lens as p_z which is a constant for the system. According to thin lens equation, to maintain the formed image in the same position no matter what objective distance p is, the lens power (ϕ_f) of the focusing lens should be:

$$\phi_f = \frac{1}{p} - \frac{1}{p_z} \tag{1}$$

Eq.(1) indicates that we can design the tunable lens power of focusing lens ϕ_f according to the range of the objective distance p and the designed formed image distance p_z. Once p_z is decided, we can start to design the zooming group in Fig. 1. The zooming function we designed is based on a confocal system. The confocal system means the formed image of the objective lens is located at the front focal plane of the eyepiece lens. We then derive the relations among p_z, the lens power of the objective lens ϕ_o and the lens power of the eyepiece lens ϕ_e in Eq. (2)

$$\begin{cases} \dfrac{1}{p_z} + \dfrac{1}{s_o} = \phi_o \\ \dfrac{1}{d - s_o} + \dfrac{1}{s_e} = \phi_e \end{cases} \tag{2}$$

where s_o is the image distance to the objective lens for the objective distance of p_z, and s_e is the image distance to the eyepiece lens which is infinity because of the confocal system. Combining two relations of Eq.(2), we obtain Eq.(3):

$$\frac{1}{p_z} + \frac{\phi_e}{\phi_e \cdot d - 1} = \phi_o \,. \tag{3}$$

For a confocal system, the magnification of the image depends of the angular magnification. The magnification of two active-optical elements in a finite objective distance can be expressed as [16]

$$M = \frac{\phi_e \times p_z}{(1 - \phi_o \times p_z)} \tag{4}$$

According to Eq. (3) and Eq. (4), we can expressed the magnification as a function of ϕ_e or as a function of ϕ_o

$$M(\phi_o) = \frac{p_z}{p_z + d - d \times p_z \times \phi_o} \tag{5}$$

$$M(\phi_e) = 1 - d \times \phi_e \tag{6}$$

When the image is erect, the magnification is positive. According to tunable range of the lens power of the active-optical elements, the magnification of the system is confined in a range between minimum magnification M_{min} and maximum magnification M_{max}. The zoom ratio (ZR) of an optical zooming system is defined as the ratio of M_{max} to M_{min}. From Eq. (1) and Eq. (4), we can adjust ϕ_f to achieve focusing function without affecting the magnification when objective distance changes. We can also adjust ϕ_o and ϕ_e to achieve zooming function without affecting the focusing distance. Thus, the focusing function and zooming function of this system are separable.

3. SIMULATION RESULTS AND DISCUSSION

3.1 Lens power of focusing lens

From Eq. (1), the lens power of focusing lens depends on the objective distance p and the designed formed image distance p_z. When the objective distance ranges from p_{min} to p_{max}, the tunable lens power of the focusing lens $\Delta\phi_f$ can be expressed as:

$$\Delta\phi_f = \frac{1}{p_{\min}} - \frac{1}{p_{\max}} \tag{7}$$

From Eq. (7), $\Delta\phi_f$ does not change as p_z changes. The ϕ_f as functions of p and p_z is calculated and plotted in Fig. 2.

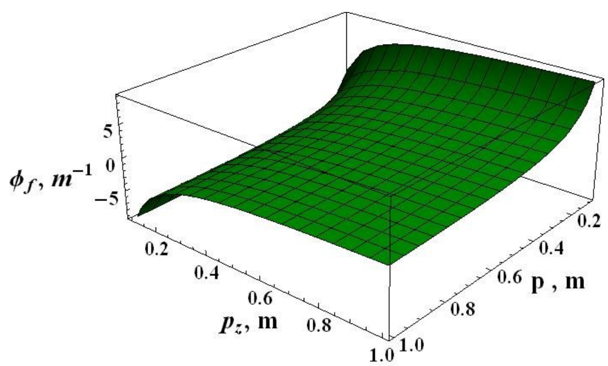

Fig. 2 The relation among the lens power of the focusing lens(ϕ_f), objective distance (p) and the formed image distance (p_z)

By choosing the range of the objective distance between p_{min} to p_{max} and the designed formed image distance p_z, we can obtain the corresponding range of lens power of the focusing lens which is also the tunable focusing range. For example, if the objective distance p is set from 10cm to infinity and p_z equals to 10cm, the tunable range of lens power of focusing lens should be from -10m^{-1} to 0 m^{-1}. But if p_z equal to 5cm, the tunable range would be from -20 m^{-1} to -10 m^{-1}. For both of the cases, the value of $\Delta\phi_f$ (=10m^{-1}) does not change.

3.2 Lens power of objective lens and eyepiece lens

In this section, we discuss the range of the lens powers for the objective lens and the eyepiece lens to obtain different zoom ratio (ZR) of the system related to p_z and d. From Eq. (5), the lens power of the objective lens can be expressed as:

$$\phi_o = \frac{M-1}{M \cdot d} + \frac{1}{p_z}. \tag{8}$$

From Eq. (6), the lens power of eyepiece lens ϕ_e can be expressed as:

$$\phi_e = \frac{1-M}{d}. \tag{9}$$

The zoom ratio (ZR) is the ratio of M_{max} to M_{min}. To simplify the discussion, we assume M_{max} equals to inverse of M_{min}. (i.e. $M_{\max} = 1/M_{\min} = \sqrt{ZR}$). From Eq. (8), the tunable lens power of the objective lens $\Delta\phi_o$ can be written as:

$$\Delta\phi_o = \frac{M_{\max}-1}{M_{\max}\cdot d} - \frac{M_{\min}-1}{M_{\min}\cdot d} = \frac{M_{\max}-M_{\min}}{M_{\max}\cdot M_{\min}\cdot d} = \frac{\sqrt{ZR}-1/\sqrt{ZR}}{d}. \tag{10}$$

From Eq. (9), the tunable lens power of eyepiece lens $\Delta\phi_e$ can be written as

$$\Delta\phi_e = \frac{1-M_{\min}}{d} - \frac{1-M_{\max}}{d} = \frac{\sqrt{ZR}-1/\sqrt{ZR}}{d}. \tag{11}$$

From Eq. (10) and Eq. (11), $\Delta\phi_o$ equals to $\Delta\phi_e$ depending on ZR and d. According to Eq. (9), Eq. (10) and Eq. (11), we can see that ϕ_e, $\Delta\phi_o$ and $\Delta\phi_e$ do not change no matter what p_z is. When the zoom ratio of the system ZR is 5 and the length of the zooming group d is 10cm, we can calculate and plot the lens powers of the objective lens and the eyepiece lens as a function of p_z , as shown in Fig. 3(a) and 3(b). From Fig. 3(a) and Fig. 3(b), the differences between two curves(the blue line and the red dotted line) remain the same ~17.9m^{-1}. This means $\Delta\phi_o$ and $\Delta\phi_e$ are maintained around 17.9m^{-1} as p_z increases. For designing the zoom system with separated focusing function and zooming function, p_z should be fixed. We can choose one specific p_z depending on the tunable lens power of active optical elements which should be capable of switching between negative lens and positive lens.

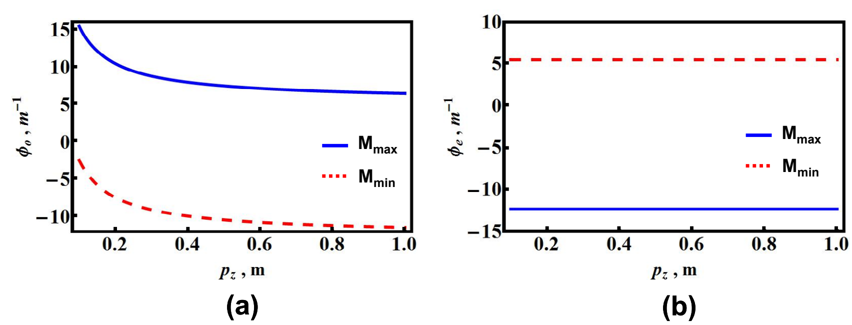

Fig. 3 (a)The lens power of the objective lens as a function of the formed image distance p_z and (b) the lens power of the eyepiece lens as a function of the formed image distance p_z for magnification M_{max} and M_{min} . ZR=5 and d=10cm.

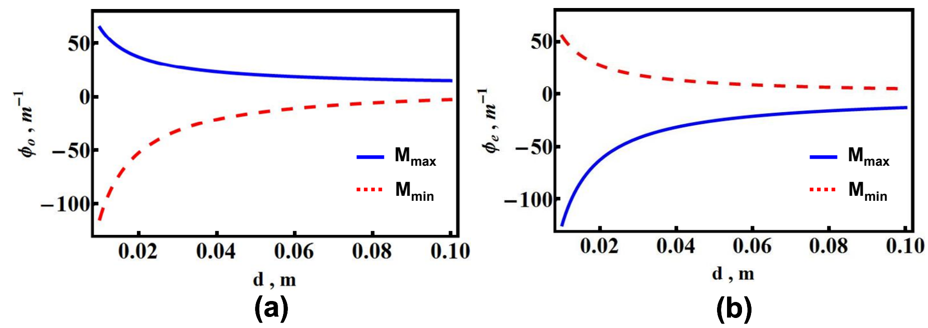

Fig. 4 (a)The lens power of the objective lens as a function of the length of zooming group d and (b) the lens power of the eyepiece lens as a function of the length of zooming group d for magnification M_{max} and M_{min} . ZR=5 an p_z =10cm.

Next, we discuss the effect caused by length of zooming group d. From Eq. (8) to Eq. (11), the absolute value of ϕ_o and ϕ_e , $\Delta\phi_o$ and $\Delta\phi_e$ increase as d decreases. When the zoom ratio of the system is 5 and p_z is 10cm, the lens power of active-optical elements in zooming group as a function of d are calculated and are shown in Fig. 4(a) and 4(b). $\Delta\phi_o$ and $\Delta\phi_e$ increase from 17.9m^{-1} to 179.9m^{-1} when d decreases from 10cm to 1cm. For applications on portable devices, a small d is preferred which means large tunable lens power of active-optical elements are very important to design the optical zoom system. For further improving the zoom ratio of the system, from Eq. (10) and Eq.(11), we also need to increase the tunable lens power range of active optical elements. For example, $\Delta\phi_o$ and $\Delta\phi_e$ should be 284.6 m^{-1} if the length of zooming group d is 1cm and the zoom ratio ZR is 10.

4. CONCLUSION

We demonstrated an electrically tunable optical zoom system with separated focusing and zooming functions. The system includes two lens groups: one is focusing group, the other is zooming group. We can separately control the focusing distance and magnification of the image by electrically tuning the lens power of active-optical elements in focusing group and zooming group. For applications on portable devices, we prefer a short system length and a large zoom ratio. According to the calculation, large tunable lens power of active optical elements is required. We can choose different active-optical elements, such as deformable mirrors, liquid lenses and liquid crystal lenses to realize the system.[6-12] This study helps designing many applications with an optical zoom function, such as cell phones, cameras, holographic projectors and endoscope.

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