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Thin and Tiny Focus-tunable Lens for Mobile Devices and Its Measurement System

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Abstract

This paper presents a thin, tiny, and electrically focus-tunable lens module for mobile devices and proposes its focal length measurement system. Previously, we have developed a thin and electrically tunable lens whose focus changes under applied voltage. One of the most important thing in developing electrically tunable lenses is to easily and conveniently measure its focal length as we change applied voltage. Therefore, we suggest a new measurement system which automatically obtains the focal length and its variation via image processing technique. The new measurement system is composed of a collimated light, a target lens, a detection screen, a camera, and a user interface software with an image processing module. We measured the focal lengths of the developed electrically tunable lens with a custom built optical setup and with the proposed system. The results with two different measurement setups for focal length addressed that the proposed system would be very helpful and effective for electrically tunable lenses in terms of swiftness, ease, and convenience. It is expected that the results of this study would be beneficial to researchers and developers in the area of thin electrically tunable lenses.

Keywords: Varifocal lens, Focus tunable, electroactive polymer, self-deformable lens.

INTRODUCTION

Considerable efforts have already been made to construct adaptive focus tunable lenses for mobile devices by methods which change the curvature of an optical medium [1-3]. Among several materials, compliant, highly transparent, and non-ionic electroactive polymers (EAPs) have been receiving a great deal of attention as a raw material for compact and tiny focus-tunable lenses [4-8]. In a typical study, a non-ionic Polyvinly chloride (PVC) gel among the EAPs has been investigated in an effort to avoid the solvent leakage because its actuation mechanism is not solvent-drag deformation but creep deformation in an electric field [8-11]. Also, the electrical actuation reduced leakage current, resulting in high energy-conversion efficiency and longer life time [8-11]. For such reasons, electrically tunable lenses based on a smart, transparent, and reconfigurable PVC gel have been developed [8,12,13,14]. In this paper, we fabricate a thin, tiny, and electrically tunable lens whose focal length's variation under voltage input is large enough to be used in applications without any external actuation devices.

One of the most important performance indexes in an electrically tunable lens is how large is the variation of the lens's focal length. There have been several research works to quantitatively measure the focal length of the electrically tunable lenses and its variation [4,15]. Ren *et al*. placed a CCD camera behind a target lens and shed collimated light on the one side of the lens, and then they computed the focal length of the lens based on the measured interference fringes at different voltages [15]. Carpi *et al*. captured the side of a target lens using a camera and calculated the focal length of a target lens based on the captured image [4].

Although these methods are so useful to investigate the focal length of a target lens, there are just a bit cases not to measure the focal length according to a system setting. Therefore, many researchers have measured the focal length of a target lens by illuminating collimated light to the lens and finding a point where collimated rays meet after passing through the lens [12-14]. The biggest benefit of this method is that a tester can easily measure the focal length of a lens regardless a system setting or a lens material property of the lens. However, since the testers measured the focal length of a target lens with naked eye, the measurement results are different depends on the testers. In order to overcome these problems, we suggest a new method which quantitatively measures the focal length of a target lens. The suggest method consists of a collimated light, a detection screen, a camera, and a user interface software with an image processing module. Performance of the system is analyzed, and experiments with electrically tunable lens is followed to examine possibility of the proposed platform as a measurement system for tunable lens's focal length.

PVC GEL LENS

Fabrication of the electrically tunable lens.

Purified PVC powder and dibutyl adipate (DBA) plasticizer were dissolved in tetrahydrofuran (THF) solution and stirred it during four hours in order to completely incorporate the DBA

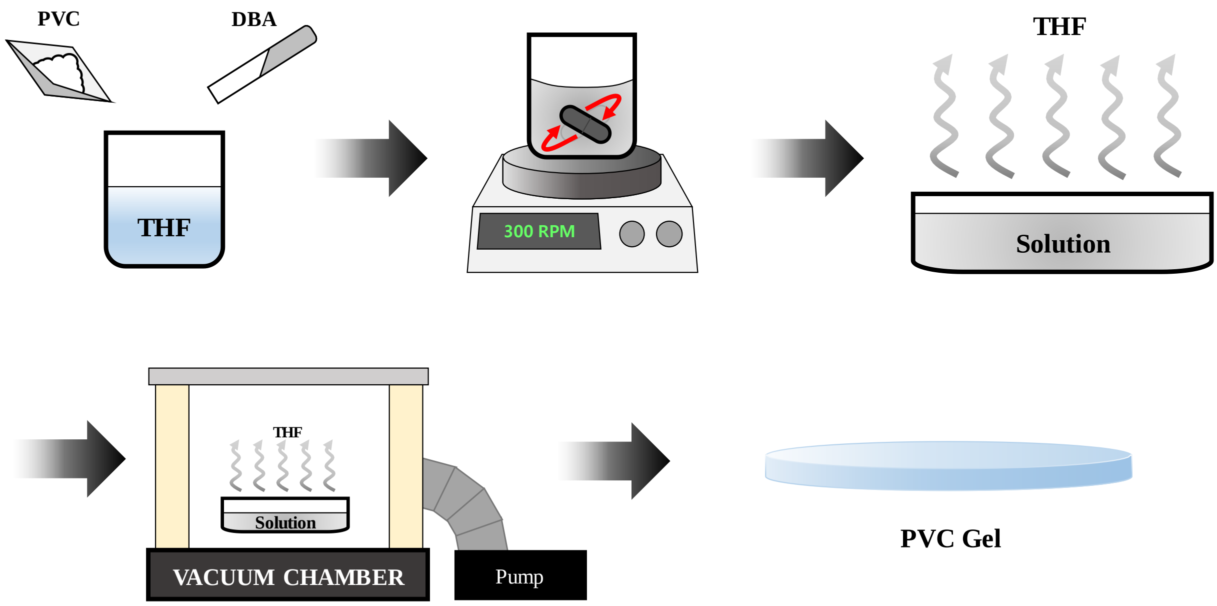
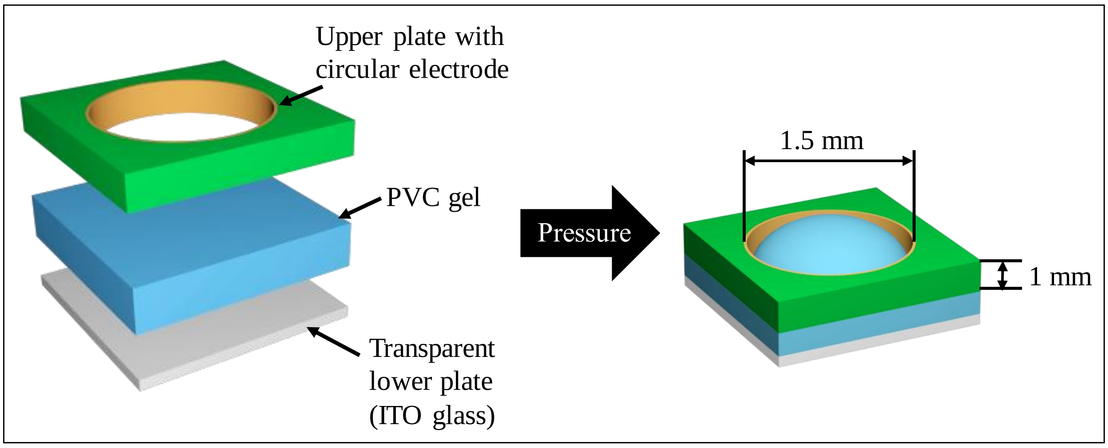


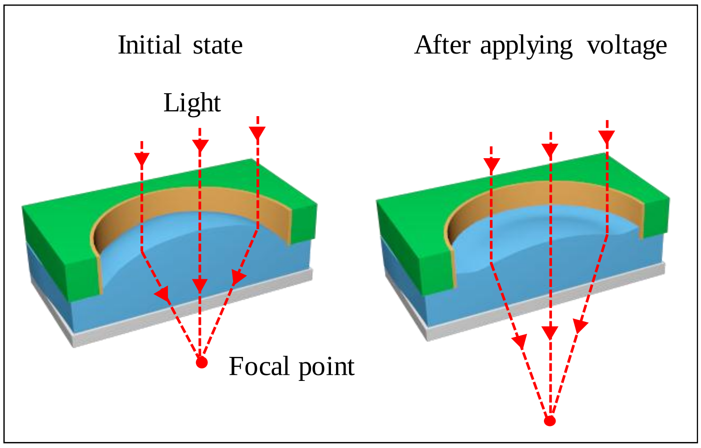
Figure 1: Fabrication process of the proposed PVC gel.

plasticizer into the PVC. We poured the uniformly mixed PVC/ DBA solution into a Teflon dish. After that we sufficiently evaporated the THF in the PVC/ DBA solution at room temperature for 72 hours and obtained a PVC gel. Figure 1 shows the fabrication process of the PVC gel.

Based on the fabricated PVC gel, we made an electroactive and reconfigurable lens. The proposed gel lens consists of an upper plate with a circular electrode, a PVC gel, and a transparent lower plate as shown in Figure 2 (a). In the upper plate, there is a hole of 1.5 mm diameter and 1 mm thickness. The inside and the edge of the hole was subsequently plated with a copper to facilitate an anode. We used an indium tin oxide coated (ITO) coated glass as the transparent lower plate. We firstly put the PVC gel onto the ITO glass and compressed the PVC gel with the upper layer to fabricate the reconfigurable lens. Finally, we could form a hemispherical plano-convex PVC gel lens within the circular aperture electrode as shown in Figure 2(a). The prepared PVC gel has distinctive deformed behavior unlike conventional non-ionic EAPs. If we apply voltage to the gel, the dipoles move toward an anode with dragging PVC chains in the gel. Due to this movement, applied voltage makes the PVC gel change the shape and the curvature, and thus leads to change its focal length as shown in Figure 2(b). Detailed information about the mechanism of the PVC gel can be found in our previous work [11].



(a)



(b)

Figure 2: The structure and the operation principle of the PVC gel lens. (a) Cross-sectional view of the proposed PVC gel lens, (b) operating principle of the proposed PVC gel lens.

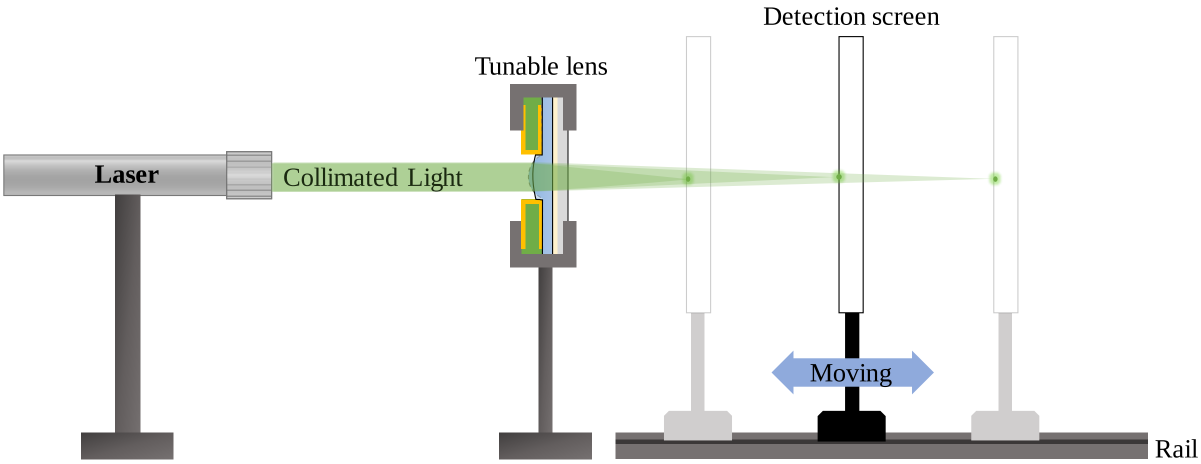


Figure 3: The conventional experimental setup for measuring the focal length of the electrically tunable lens.

Custom built optical setup for measuring focal length of the PVC gel lens

The focal length of the electrically tunable lenses is usually measured by a custom built optical setup consisting of a tunable lens, a collimated light, and a detection screen as shown in Figure 3. We shed collimated light on the one side of the lens and the output ray through the lens was directed onto the detection screen. We found the smallest fine spot of the collimated light as we moved the detection screen, and then we measured the distance between the center of the electrically tunable lens and the detection screen with the smallest spot. If voltage input is applied to the electrically tunable lens, focal point is changed and detection screen is moved to another position in order to have the smallest spot. Generally, the focal length of a lens is computed using (1). In (1), since we used collimated light, the distance between a target object and the center (O) of the lens is considered as infinity. That is (1/A) in (1) becomes zero.

$$\frac{1}{F}=\frac{1}{A}+\frac{1}{B} \qquad (1)$$

where,

F : focal length of the electrically tunable lens,

A: distance between a target object and the center (O) of the lens,

B: distance between O and the detection screen with the smallest fine spot.

NEW MEASUREMENT SYSTEM FOR INVESTIGATING FOCAL LENGTH OF THE TUNABLE LENS.

The previous measurement system can be easily constructed, however, the focal point can vary each time the testers measure it. Furthermore, it can be hardly accurately measured by the testers. The reason is that the smallest fine spot of the collimated light on the detection screen has to be found with the naked eye. In order to solve the problems, we suggest a new measurement system which helps us to easily and consistently measure the focal length of the electrically tunable lens. The proposed system has a huge merit in that we do not need to move the detection screen and also do not need to find the exact position of the detection screen with smallest fine spot of the collimated light. The proposed system is composed of a collimated light, a target lens, a detection screen, a camera, and a PC having an image processing software module as shown in Figure 4.

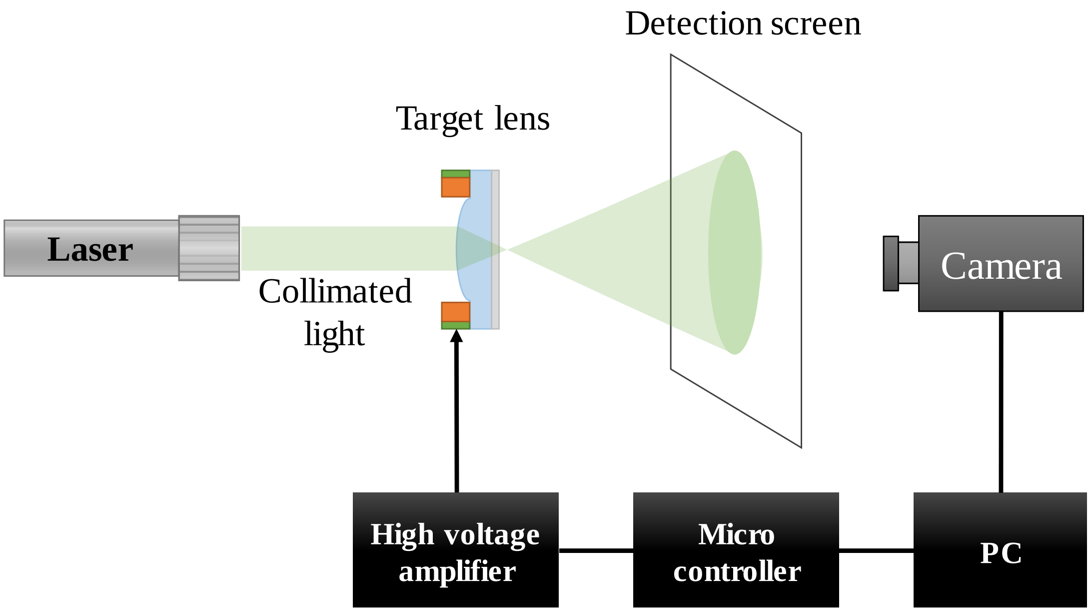


Figure 4: The proposed measurement system.

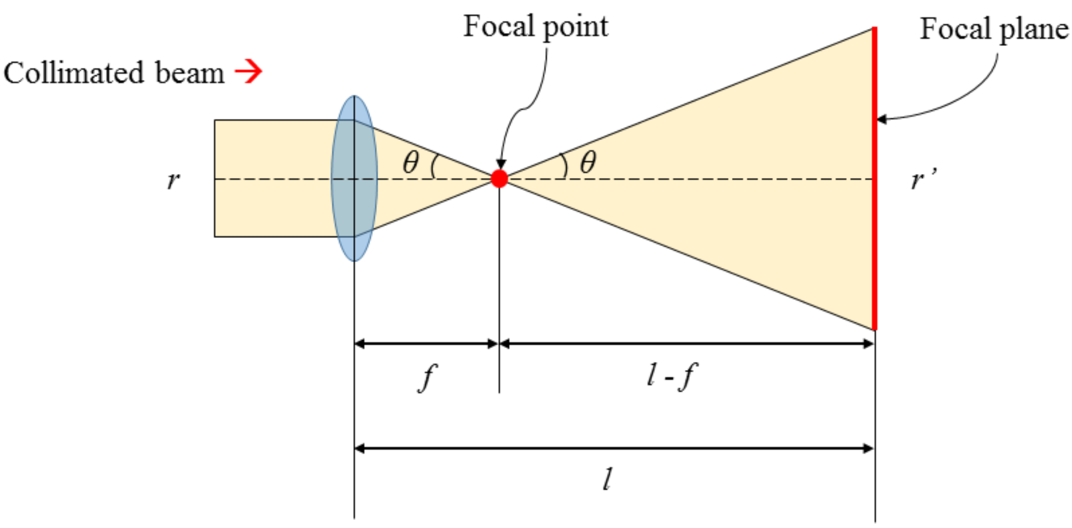


Figure 5: Pathway of the light source.

The collimated monochrome light originated from the laser was in concordance with the optic axis of the electrically tunable lens and the light was shed on the one side of the lens. The focal point was positioned between the lens and the detection screen and the reverse image through the lens was projected on the detection screen. The reverse image on the detection screen was captured by the camera and was transferred to the PC. In the PC, the focal length of the lens was computed by investigating the image. We drew the pathway of the collimated light after passing through the lens (Figure 5). In Figure 5, r and r' are the diameters of the collimated monochrome light source and the image on the detection screen, respectively, and f is the focal length of the lens, and the angle (θ) that the light spreads out can be computed by (2) which shows the relationship between the focal length (f) and other lens variables (*l*, r, and r'). From (2), we can easily obtain the focal length of the lens if we measure the above three lens variables.

$$\tan\theta = \frac{f}{\frac{r}{2}} = \frac{l - f}{\frac{r'}{2}} = 1 \qquad (2)$$

$$f = l \times \frac{r}{r + r'} \quad (r' > 0) \qquad (3)$$

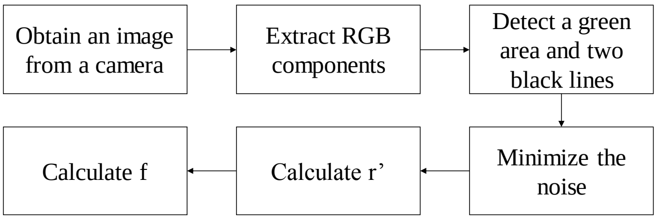
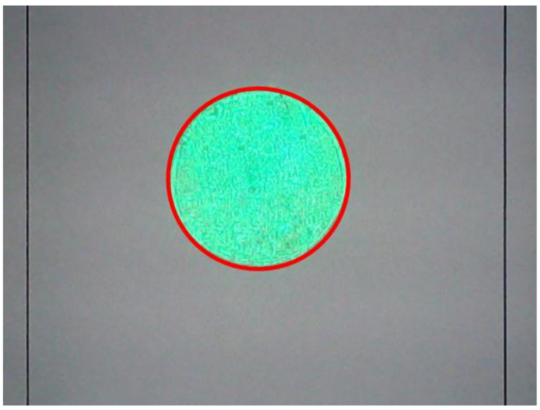
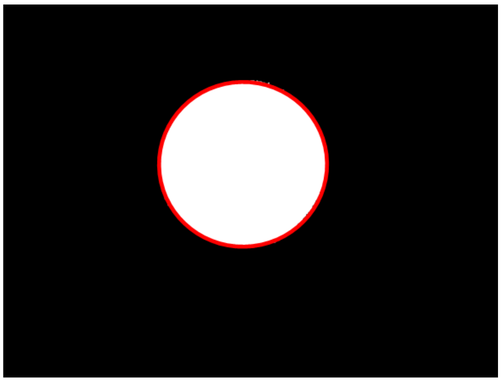


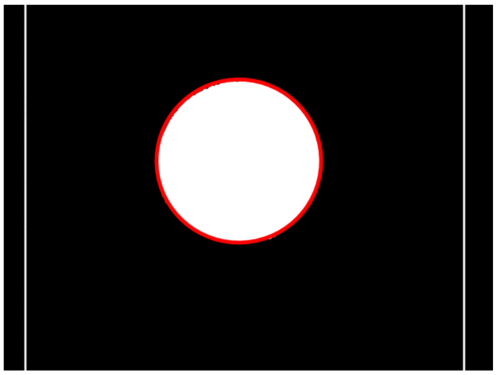
Figure 6: Block diagram for computing focal length of a target lens.



(a)



(b)



(c)

Figure 7: Detected light spot.

Figure 6 shows the block diagram for measuring the focal length of the target lens. First, we drew two vertical lines, whose color is black, on a paper and attached the paper to the detection screen. The distance between two vertical lines is 80 mm. When the image through the lens is displayed on the paper, the displayed image is captured the camera as shown in Figure 7(a). As we mentioned before, the proposed system used a collimated monochrome green light (532 nm). So, we detected portions where green and black colors are dominant through the global fixed binarization [13] after extracting RGB color components in the displayed image. Morphology open operation [13] was applied to the system to minimize the noise caused from global fixed binarization (Figure 7(b)). We computed the diameters (r') of the image on the detection screen in millimeter. Figure 7(c) shows the light spot image with two lines on the detection screen. Finally, we calculated the focal length of the lens using equation (3).

EXPERIMENT AND RESULT

User interface software

The main purpose of the proposed system is to accurately and consistently measure the focal length of the electrically tunable lens. As we increase the voltage input to the electrically tunable lens, the PVC gel increasingly moves to anode and its curvature decreases. As a result, the focal length of the electrically tunable lens increases. In this experiment, initial focal length of the electrically tunable lens was set as 3 mm and the distance (*l*) between the lens and the detection screen is determined as 15 mm. Furthermore, the applied voltage was varied in the range of 100 V to 800 V at 100 V intervals for measuring focal length variation of the developed electrically tunable PVC gel lens.

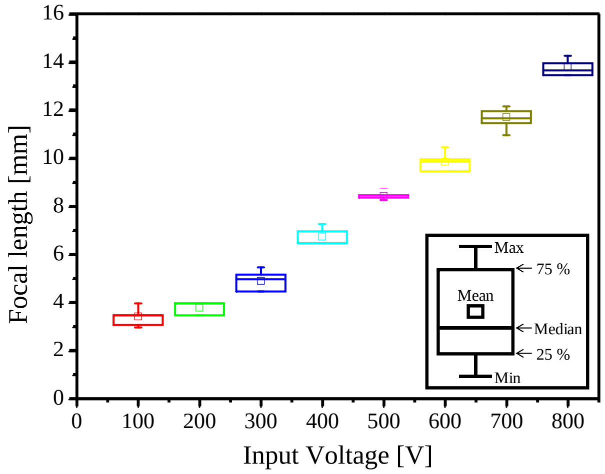
A user interface software (Figure 8) was developed to easily and conveniently interact with the proposed measurement system. The user interface software was developed by a program written in C#. The experiment was conducted using a PC with an i5 2.5GHz dual core processor. The user interface consists of an initialization part (①), a confirmation part(②), a control panel part(③), and a displaying part (④). A tester filled in the distance (*l*) between the lens and the detection screen, and the diameter of the collimated light (r) through the initialization part. The confirmation part is a portion where a tester checks input image through the camera and he/she verifies the projected image with two vertical lines on the detection screen using image processing in real-time. Part ③ is a control panel for connecting a microprocessor and a PC and for applying voltage input to the target lens. The process to measure the focal length of the PVC gel lens commences by pushing the “start” button. The measured focal length is displayed in the region ④ and is saved as a spread sheet file format when the ‘save’ button is clicked.

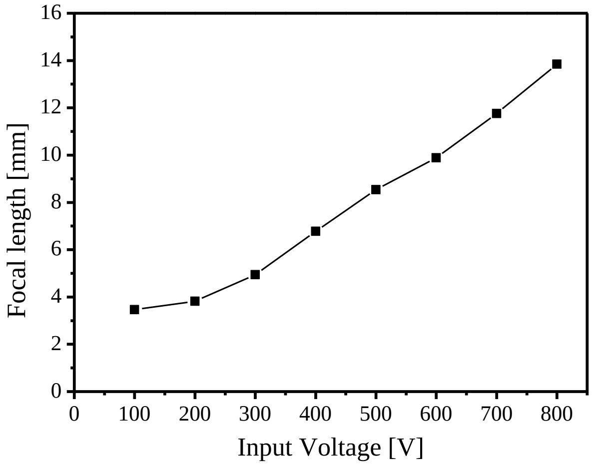
Figure 8: Developed user interface

Results of focal length

We investigated the focal length of the electrically tunable PVC gel lens with two different experimental setups (one is a custom built optical setup and the other is the proposed system). The focal length with the custom built optical setup was measured 10 times and the measurement with the proposed system was conducted only one time. We plotted the measured focal length with the custom built optical setup and the measured another focal length from the proposed system for easy comparison in Figure 9. Figure 9(a) shows the results of measured focal lengths with the custom built optical setup. As we mentioned before, we moved the detection screen until the smallest spot of collimated light could be observed whenever we applied the voltage from 100 V to 800 V. After that, we computed the focal length of the target lens using (1).

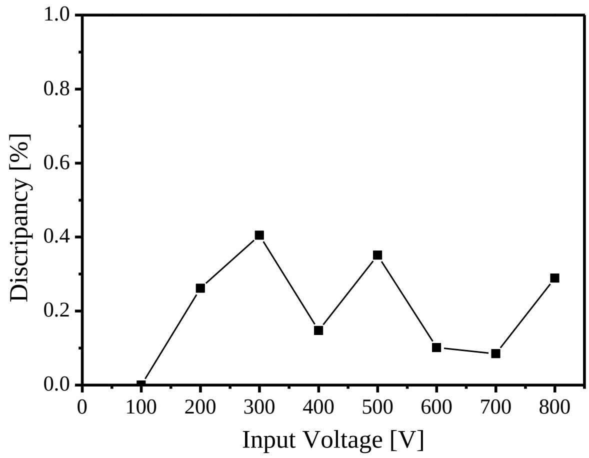
The focal length continuously increased from 3.46 mm to 13.85 mm with increasing applied voltages from 100 V to 800 V. Figure 9(b) shows the results of the measured focal lengths with the proposed system. It seems that the mean values of the measured focal lengths by the custom built optical setup were almost same as the focal lengths by the proposed system. We investigated how difference they are by computing errors (Figure 9(c)). The result shows that it has a maximum 0.4% margin of error. It seems that there is no difference between two results (Figure 9(a) and Figure 9(b)). We investigated that the average value from a custom built optical setup and then we compared the average value and the data obtained from the proposed method using a T-test with a null hypothesis: there is no difference between two results (Figure 9(a) and Figure 9(b)). Probability values (p-value) for all voltage inputs were computed and tabulated in Table 1. The null hypothesis is accepted at a significance level α=0.05 for all voltage inputs. Since the two results are statistically same, it is concluded that the proposed system can clearly measure the focal length of the electrically tunable lens.





(a) (b)

(b)



(c)

Figure 9: Results of measured focal length (a) : using custom built optical setup, (b) : using the proposed system, (c) : errors between the two results.

Table 1: Probability values for all inputs

Input [V]	100	200	300	400	500	600	700	800
p-value	0.5	0.44892	0.43035	0.46029	0.19782	0.46267	0.34804	0.34804

Results of Zooming Effect

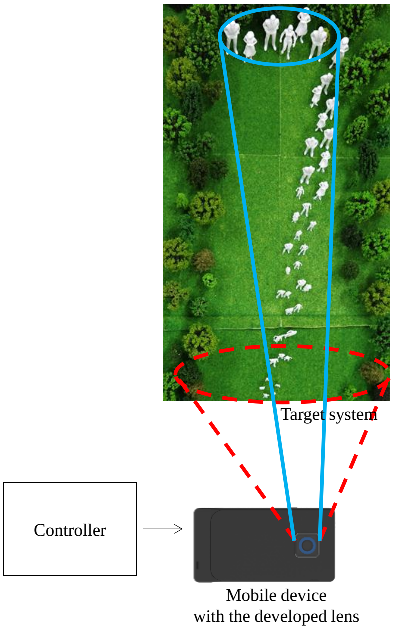


Figure 10: Experimental setup for measuring focal point

To qualitatively investigate the focal length's variation of the proposed tunable PVC gel lens, we inspected zooming effect using an experimental setup consisting of a controller, a mobile device with the developed varifocal lens, and a target system as shown in Figure 10. Initially, the focal point of the developed lens is on the forefront objects (marked as a red dashed line) in the target system. As we increase the voltage input, the focal point is gradually moved to the backward (marked as a cyan line). Figure 11 shows the results of the image obtained through the PVC gel lens with varying applied voltages.

(a) (b)

Figure 11: Qualitative results of the developed PVC gel lens according to the applied electric fields.

CONCLUSION

In this paper, we fabricated a compact, transparent, and electrically tunable PVC gel lens module for mobile devices and suggested the focal length measurement system for the electrically tunable PVC gel lens. The proposed measurement system overcomes a conventional custom built optical setup's drawback (the measured focal length can be different according to testers). Other advantages are that the proposed system can protect the tester's eye against laser light beams and can reduce the measurement time. It is expected that the results of this work would be beneficial to researchers in the area of electrically tunable lenses.

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