# MULTIFUNCTIONAL LIQUID LENS (MLL) FOR VARIABLE FOCUS AND VARIABLE APERTURE

*Jeongmin Lee, Yuna Park, Sang Hoon Oh, and Sang Kug Chung*
Myongji University, Yongin, Gyeonggido, South Korea

## ABSTRACT

This paper presents a novel multifunctional liquid lens (MLL) based on electrowetting-on-dielectric (EWOD) actuation for high-performance miniature cameras. MLL firstly offers variable-focus and variable-aperture functions in a single lens system using sole EWOD actuation. The performance of MLL consisting of lens and iris units is experimentally verified. The variable-focus function of the lens unit and variable-aperture function of the iris unit are separately investigated using a prototype of MLL. Finally, as proof of concept, the simultaneous operations of variable-focus and variable-aperture functions of MLL are experimentally demonstrated using two transparent optical charts with the cloud and sun image.

## INTRODUCTION

With the enormous demand of mobile devices such as smartphones and pads, the development of small but high-performance miniature cameras has been a tremendous issue [1, 2]. However, the conventional tunable optical systems relied on solid lenses and mechanical actuators have reached the limit of further miniaturization and performance because of their structural problems.

A typical variable-focus optical system changes an optical focal length by controlling the distance of solid lenses using a mechanical actuator. It is usually bulky, heavy, and complicated because of the fabrication and assembly of tiny mechanical and electrical components (e.g. motors, gears, etc.) [3]. Similarly, a typical variable-aperture optical system changes an optical aperture to regulate the light intensity and depth of field (DOF) using mechanically movable blades. Hence, it is not only bulky but also slow due to its complicated sliding rotary mechanism [4, 5].

To overcome the limits of the conventional tunable optical systems, liquid based optical systems have emerged and attracted great attentions from optical and microelectromechanical systems (MEMS) societies as a promising solution, owing to their advantages such as compact size, fast response time, and absence of moving parts [6]. Many research groups have investigated various types of liquid lenses and liquid irises. For instance, a liquid crystal lens [7, 8], fluidic lens [9], dielectric lens [10, 11], and etc. have been developed for the variable-focus liquid lenses.

Electrowetting-on-dielectric (EWOD) inducing the modification of the wetting properties of a solid surface from hydrophobic to hydrophilic with an applied electric field is one of the most attractive technologies to control the liquid lens [12]. Berge and Peseux firstly developed the EWOD driven liquid lens composed of two immiscible liquids with different refractive indices [13]. Since then, a number of liquid lenses based on EWOD actuation have been developed due to its outstanding advantages such as simple fabrication, fast response time, and low power consumption [14-16].

The variable-aperture liquid iris can be classified by its working principle into three categories: pneumatic actuation [17], electromagnetic actuation [2, 18], and EWOD actuation [19-21]. Müller et al. developed a liquid iris operated by EWOD actuation inducing the deformation of a ring-shaped liquid-liquid interface for changing the aperture [22]. Xu et al. also developed a similar EWOD driven liquid iris using radial-interdigitated patterned electrodes to achieve the fast response time [23].

Although various liquid lenses and irises have been developed up to now, all kinds of the liquid lenses and irises fulfill only a single optical function – variable-focus or variable-aperture. Hence, it requires additional actuators and systems for the other optical function, which makes the total size of the miniature camera bulky and heavy again. To resolve the issue, Chung research group firstly proposed the concept of the multifunctional liquid lens (MLL) and developed the 1st version of MLL providing concurrent variable-focus and variable-zoom functions in a single lens system using both EWOD actuation for controlling the lens curvature and electromagnetic actuation for controlling the lens position, along with experimental verification [24]. Note that the work was selected as the outstanding paper award finalist in 2016 IEEE MEMS.

In this paper, we firstly present the 2nd version of MLL providing concurrent variable-focus and variable-aperture functions in a single lens system using sole EWOD actuation, which can significantly reduce the total size of miniature cameras. Figure 1 shows the schematic diagram of the 2nd version of MLL consisting of lens and iris units. When a voltage is applied to an EWOD electrode on the inclined sidewall of the lens unit, the curvature of the liquid-liquid interface is modified according to EWOD principle, changing the focal length. Hence, an initially blurred check-pattern image is focused clearly in Fig. 1(a-b). When a voltage is sequentially applied to patterned ITO EWOD electrodes of the iris unit, opaque liquid

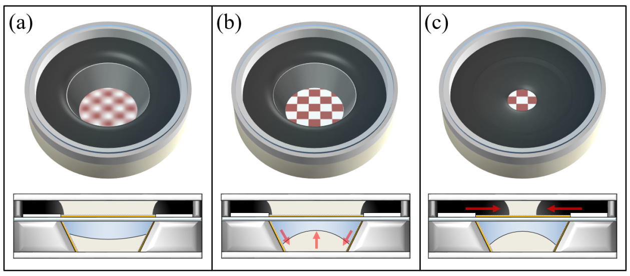


*Figure 1: Schematic diagram of multifunctional liquid lens (MLL) based on sole electrowetting-on-dielectric (EWOD) actuation: (a) Initial state; (b) Variable-focus function; (c) Variable-aperture function.*

initially covering only in the rim of the iris shifts to the center of the iris, changing the aperture diameter of the iris in Fig. 1(c). The proposed MLL provides a simple design to be easily miniaturized but covers a wide range of variable-focus and variable-aperture functions for high-performance miniature cameras.

## DESIGN AND FABRICATION

The schematic exploded diagram of MLL with the detailed design of EWOD electrodes is illustrated in Fig. 2. The proposed MLL consists of two optical units – lens unit for a variable-focus function and iris unit for a variable-aperture function. First, the lens unit has a cone-shaped lens body made of Polydimethylsiloxane (PDMS) with the inclined sidewall covered with transparent indium tin oxide (ITO) as a metal electrode layer, parylene-C layer as a dielectric layer, and Cytop (CTL-809M + CT-Solv.180, Asahi Glass Co., Ltd.) as a hydrophobic layer in series for EWOD actuation. Second, the iris unit consists of a middle plate with patterned ITO electrodes for sequential EWOD actuation, an acrylic body manufactured by a laser cutter (IS-640, Innosta Co.) for containing opaque liquid, and a top plate covered with an ITO electrode for the ground electrode.

The patterned ITO electrodes in the middle plate were microfabricated by standard MEMS fabrication processes, as shown in Fig. 3. First, a glass slide was cleaned for 10 min in a heated piranha solution, blow-dried by nitrogen gas, and dehydrated for 30 min on a hot plate. An ITO layer was deposited on a glass slide with 30 nm thickness of a structure layer by using a sputter. A photoresist (AZ 7220) layer was spin-coated with 2500 rpm for 20 sec on the ITO electrode layer and soft baked for 90 sec at 90 °C. After that, the photoresist was patterned by photolithography processes. Subsequently, the ITO electrodes were wet etched using ITO etchant to form ring-shaped transparent electrodes with width of 450 μm and gap of 50 μm between the adjacent electrodes. After removing the remaining photoresist, an insulating layer of parylene-C (2.5 ± 0.1 μm thick) was deposited using chemical vapor deposition (CVD), and a hydrophobic layer of Cytop was spin-coated on the dielectric layer. Finally, a ring-shaped PET film was placed around the patterned ITO electrodes for obtaining hydrophilicity to hold the initial position of opaque liquid.

Figure 4 shows the schematic diagrams of two different units of MLL and their working principles. For the liquid lens unit, two different immiscible liquids are used: water-based conducting liquid and oil-based insulating liquid, which have about the same density but

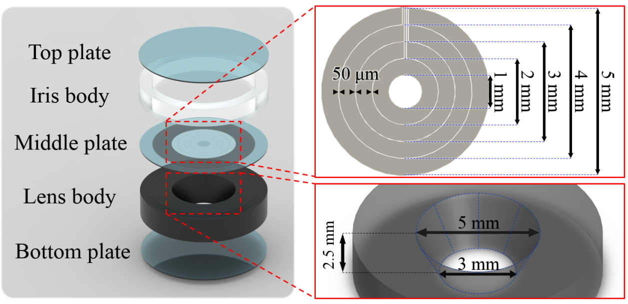


*Figure 2: Schematic exploded diagram of MLL.*

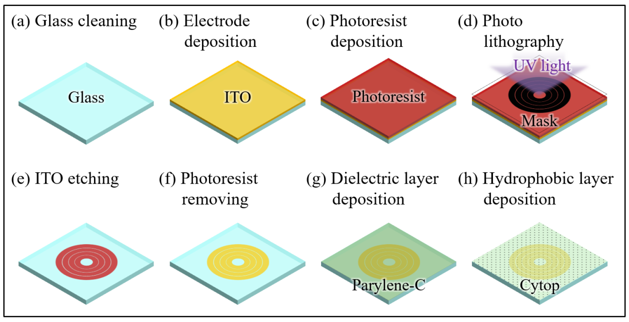


*Figure 3: Schematic images of microfabrication processes.*

different refractive indices. When a voltage is applied to an electrode covered with a hydrophobic dielectric layer on the inclined sidewall of the lens unit, the contact angle of conducting liquid is modified according to EWOD principle, changing the curvature of the liquid-liquid interface, as shown in Fig. 4(a). As a result, the focal length of the lens unit is modified.

The liquid iris unit consists of conducting liquid (opaque ink) for absorbing light and insulating liquid (transparent oil) for defining the aperture. The conducting liquid is initially positioned on the ring-shaped hydrophilic PET film, and the insulating liquid is filled in the rest space of the iris unit, as shown in Fig. 4(b). When an electrical voltage is sequentially applied to patterned ITO electrodes covered with a hydrophobic dielectric layer inside the liquid iris unit, the opaque conducting liquid, initially covering only on the rim of the iris unit, shifts to the center of the iris unit, resulting that the aperture diameter of the iris unit is modified.

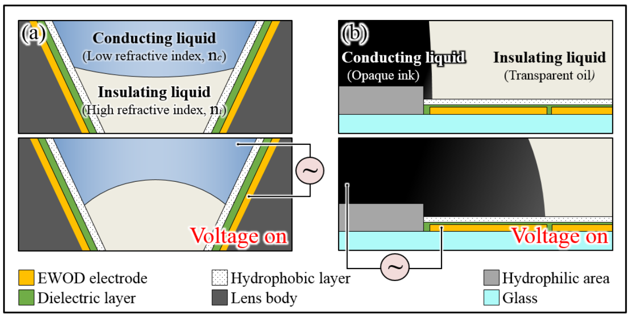


*Figure 4: The operation mechanism of MLL: (a) Variable-focus function; (b) Variable-aperture function.*

## EXPERIMENTAL SETUPS

Figure 5 shows the schematic diagram of experimental setups mainly consisting of electrical and optical systems. For EWOD actuation, a sinusoidal voltage (1 kHz) is generated by a function generator (33210A, Agilent Co.), and amplified by a voltage amplifier (PZD700, Trek Co.). The electrical signal is transmitted to the electrodes through photo-coupled relays (PhotoMos®, AQW614EH, Aromat Co.) controlled by a digital input/output board (DAQ pad-6229 BNC, NI Co.) with a programmed LabVIEW code. All experimental images are captured by using a charge-coupled device (CCD) camera (EO-1312C, Edmund Optics) integrated with a zoom lens (VZMTM 450i eo, Edmund Optics), and saved on a personal computer.

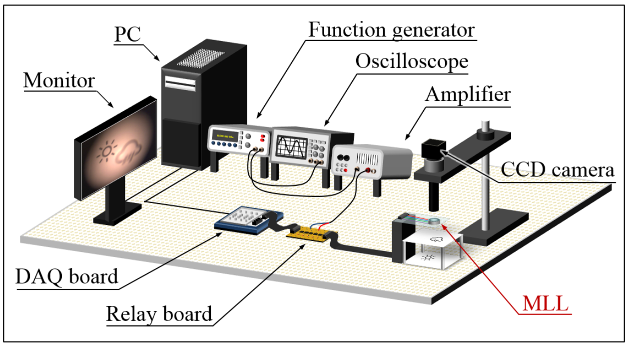


*Figure 5: Schematic diagram of experimental setups.*

## EXPERIMENTAL RESULTS

To evaluate the variable-focus function of the lens unit of MLL, an image focusing test is carried out in Fig. 6. The focal length in the lens unit depends on the curvature of the liquid-liquid interface which initially forms a concave surface profile with a negative focal length. When a voltage is applied to the EWOD electrode on the inclined sidewall of the lens unit, the curvature profile is changed to convex by EWOD principle, resulting in modifying the focal length. For the test, an optical chart is placed 10 cm apart from MLL. The optical chart is initially blurred in Fig. 6(a). When a proper voltage (60 V) is applied to the EWOD electrode of the lens unit, the optical chart is focused clearly as the curvature of the liquid-liquid interface is modified, as shown in Fig. 6(b).

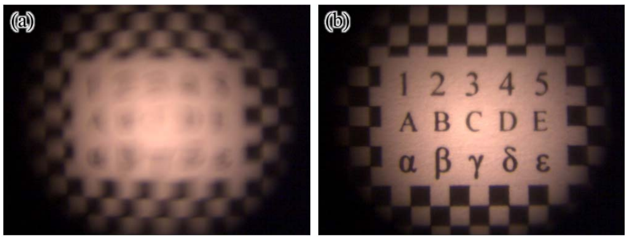


*Figure 6: Image focusing test of the lens unit of MLL: (a) An optical chart is initially blurred; (b) When a proper voltage (60 V) is applied to the variable-focus liquid lens unit of MLL, clear characters in the optical chart are acquired.*

The operation test of the iris unit of MLL is also carried out by using methylene blue solution as opaque liquid and silicone oil (Xiameter®, PMX-200 1 CS) as transparent ambient liquid, as shown in Fig. 7. In the initial state, the opaque liquid inside the iris unit is in a relaxed state, so the iris unit shows the largest aperture (5.0 mm). When a voltage (90 V) is applied to the EWOD electrode, the opaque liquid, which is initially placed on the rim of the iris unit, is actuated and pulled toward the activated electrode by EWOD principle. To reduce the aperture of the iris unit, an electrode adjacent to the opaque liquid is activated. Then the opaque liquid is immediately pulled to the activated electrode. By shifting and repeating this procedure to the most inner electrode in the patterned EWOD electrodes, the smallest aperture (1.04 mm) of the iris unit is achieved, as shown in Fig. 7(d). The tunable aperture diameter of the iris unit ranges from 5.0 mm to 1.04 mm.

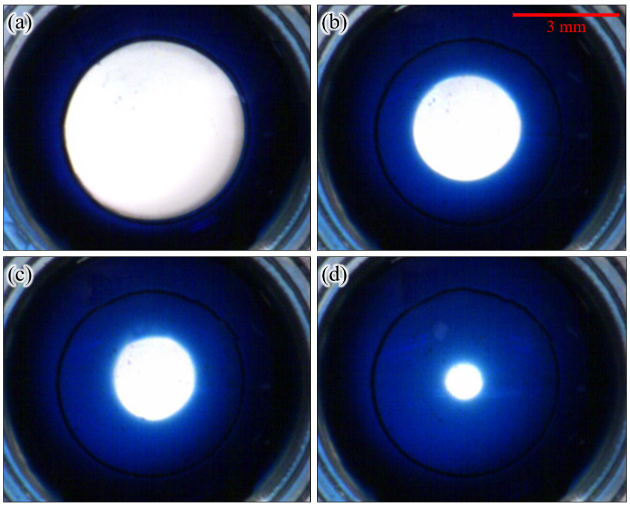


*Figure 7: The operation test of the iris unit of MLL.*

Finally, as proof of concept, simultaneous variable-focus and variable-aperture functions of MLL are successfully demonstrated. For the test, two transparent optical charts with each cloud and sun image are respectively located 10 cm and 28 cm apart from MLL, and a CCD camera is used for capturing optical images, as shown in Fig. 8(a). When a voltage (30 V) is applied to the EWOD electrode in the lens unit of MLL, the sun image is focused, but the cloud image is blurred in Fig. 8(b1). Subsequently, when the applied voltage is changed to 60 V, the cloud image is focused clearly but the sun image is simultaneously blurred as the curvature of the liquid-liquid interface is modified in Fig. 8(b2). In addition, when an electrical voltage (120 V) is sequentially applied to the patterned EWOD electrodes in the liquid iris unit, opaque conducting liquid shifts to the center of the iris unit, resulting that the aperture diameter of the iris unit is modified in Fig. 8(b3).

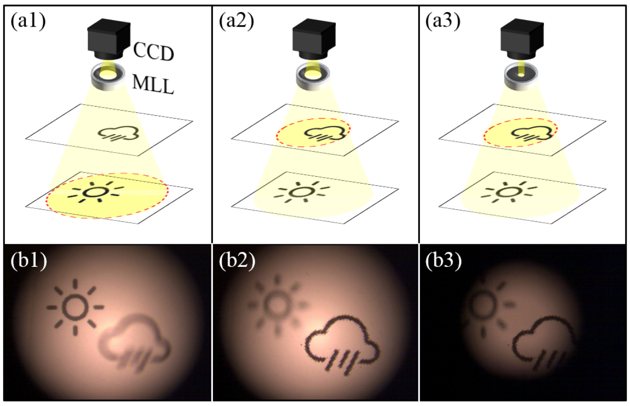


*Figure 8: Demonstration of the integrated functions of MLL: (a) Schematic diagram of the optical test; (b1) The sun image is firstly focused and simultaneously the cloud image is blurred by applying 30 V to the electrode in the lens unit; (b2) On the other hand, the cloud image is focused and the sun image is blurred by applying 60 V; (b3) When an electrical voltage is sequentially applied to the patterned EWOD electrodes in the liquid iris unit, opaque conducting liquid shifts to the center of the iris unit, resulting that the aperture diameter of the iris unit is changed.*

## CONCLUSION

This paper presents a novel multifunctional liquid lens (MLL) for variable-focus and variable-aperture functions based on sole electrowetting-on-dielectric (EWOD) actuation. The optical functions of MLL are separately verified using a prototype of MLL. First, an image focusing test is conducted to examine the performance of the liquid lens unit. When a voltage is applied to the EWOD electrode in the lens unit, the curvature of the liquid-liquid interface is modified according to EWOD principle. As a result, an initially blurred optical chart is focused clearly. Second, the operation test of the liquid iris unit is carried out by using methylene blue solution as opaque liquid and silicone oil as transparent ambient liquid. When an electrical voltage is sequentially applied to the patterned EWOD electrodes in the iris unit, opaque conducting liquid shifts to the center of the iris unit, resulting that the aperture diameter of the iris unit is modified. The tunable aperture diameter of the iris unit ranges from 5.0 mm to 1.04 mm. Finally, the simultaneous operation of variable-focus and variable-aperture functions are successfully demonstrated by sole EWOD actuation. The proposed MLL offers a simple design to be easily miniaturized but covers a wide range of focal lengths and apertures.

## ACKNOWLEDGEMENTS

This work was supported by Basic Science Research Program (2015R1D1A1A02062153) of the National Research Foundation of Korea (NRF) funded by the Ministry of Education and 2016 Research Fund of Myongji University.

## REFERENCES

[1] N.-T. Nguyen, "Micro-optofluidic Lenses: A Review", *Biomicrofluidics*, vol. 4, p. 031501, 2010.
[2] H. W. Seo, J. B. Chae, S. J. Hong, K. Rhee, J.-H. Chang, S. K. Chung, "Electromagnetically Driven Liquid Iris", *Sens. Actuators A-Phys.*, vol. 231, pp. 52-58, 2015.
[3] S. Xu, H. Ren, S.-T. Wu, "Dielectrophoretically Tunable Optofluidic Devices", *J. Phys. D-Appl. Phys.*, vol. 46, p. 483001, 2013.
[4] H. Yu, G. Zhou, Y. Du, X. Mu, F. S. Chau, "MEMS-based Tunable Iris Diaphragm", *J. Microelectromech. Syst.*, vol. 21, pp. 1136-1145, 2012.
[5] S. Kuiper, B. H. W. Hendriks, "Variable-focus Liquid Lens for Miniature Cameras", *Appl. Phys. Lett.*, vol. 85, pp. 1128-1130, 2004.
[6] L. Li, C. Liu, H. Ren, Q.-H. Wang, "Adaptive Liquid Iris Based on Electrowetting", *Opt. Lett.*, vol. 38, pp. 2336-2338, 2013.
[7] H. Ren, D. W. Fox, B. Wu, S.-T. Wu, "Liquid Crystal Lens with Large Focal Length Tunability and Low Operating Voltages", *Opt. Express*, vol. 15, pp. 11328-11335, 2007.
[8] M. Ye, B. Wang, S. Sato, "Liquid-crystal Lens with a Focal Length that is Variable in a Wide Range", *Appl. Optics*, vol. 43, pp. 6407-6412, 2004.
[9] F. Schneider, C. Müller, U. Wallrabe, "A Low Cost Adaptive Silicone Membrane Lens", *J. Opt. A: Pure Appl. Opt.*, vol. 10, p. 044002, 2008.
[10] S. Xu, Y.-J. Lin, S.-T. Wu, "Dielectric Liquid Microlens with Well-shaped Electrode", *Opt. Express,* vol. 17, pp. 10499-10505, 2009.
[11] C.-C. Cheng, J. A. Yeh, "Dielectrically Actuated Liquid Lens", *Opt. Express*, vol. 15, pp. 7140-7145, 2007.
[12] A. Shahini, J. Xia., Z. Zhou, Y. Zhao, M. M.-C. Cheng, "Versatile Miniature Tunable Liquid Lenses Using Transparent Graphene Electrodes", *Langmuir*, vol. 32, pp. 1658-1665, 2016.
[13] B. Berge, J. Peseux, "Variable Focal Lens Controlled by an External Voltage: An Application of Electrowetting", *Eur. Phys. J. E*, vol. 3, pp. 159-163, 2000.
[14] C.-P. Chiu, T.-J. Chiang, J.-K. Chen, F.-C. Chang, F.-H. Ko, C.-W. Chu, S.-W. Kuo, S.-K. Fan, "Liquid Lenses and Driving Mechanisms: A Review", *J. Adhes. Sci. Technol.*, vol. 26, pp. 1773-1788, 2012.
[15] J. T. Gopinath, V. M. Bright, C. C. Cogswell, R. D. Niederriter, A. Watson, R. Zahreddine, R. H. Cormack, "Simulation of Electrowetting Lens and Prism Arrays for Wavefront Compensation", *Appl. Optics*, vol. 51, pp. 6618-6623, 2012.
[16] C. Li, H. Jiang, "Fabrication and Characterization of Flexible Electrowetting on Dielectrics (EWOD) Microlens", *Micromachines*, vol. 5, pp. 432-441, 2014.
[17] Y. Hongbin, Z. Guangya, C. F. Siong, L. Feiwen, "Optofluidic Variable Aperture", *Opt. Lett.*, vol. 33, pp. 548-550, 2008.
[18] H. Yu, G Zhou, F. S. Chau, S. K. Sinha, "Tunable Electromagnetically Actuated Liquid-filled Lens", *Sens. Actuators A-Phys.*, vol. 167, pp. 602-607, 2011.
[19] L. Li, C. Liu, Q.-H. Wang, "Optical Switch Based on Tunable Aperture", *Opt. Lett.*, vol. 37, pp. 3306-3308, 2012.
[20] J.-H. Chang, K.-D. Jung, E. Lee, M. Choi, S. Lee, W. Kim, "Variable Aperture Controlled by Microelectrofluidic Iris", *Opt. Lett.*, vol. 38, pp. 2919-2922, 2013.
[21] C.-C. Yu, J.-R. Ho, J.-W. J. Cheng, "Tunable Liquid Iris Actuated Using Electrowetting Effect", *Opt. Eng.*, vol. 53, p. 057106, 2014.
[22] P. Müller, R. Feuerstein, H. Zappe, "Integrated Optofluidic Iris", *J. Microelectromechanical Syst.*, vol. 21, pp. 1156-1164, 2012.
[23] M. Xu, H. Ren, Y.-H Lin, "Electrically Actuated Liquid Iris", *Opt. Lett.*, vol. 40, pp. 831-834, 2015.
[24] I. S. Park, J. W. Yang, S. H. Oh, S. K. Chung, "Multifunctional Liquid Lens for High-performance Miniature Cameras", in *MEMS'16 Conference,* Shanghai, January 24-28, 2016, pp. 776-779.

## CONTACT

*S. K. Chung, tel: +82-31-330-6346; skchung@mju.ac.kr