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Characterization of adjustable fluidic lenses and capability for aberration correction of defocus and astigmatism

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ABSTRACT

An adjustable, variable-focus fluidic lens is typically utilizing curvature change in the meniscus between two immiscible liquids or by adjusting the liquid pressure of the lens chamber. In addition, this curvature change can be used as a deformable mirror to correct the aberrations such as defocus and astigmatism. In this paper, we first fabricate a liquid lens prototype and experimentally characterize relevant optical performance such as focal length tunability over curvature change through adjusted liquid volume. Moreover, capability of adjustable fluidic lenses to correct the induced wavefront aberrations is investigated systematically, with particular attention placed on interpretation of Zernike modes and fully explores the potentials of fluidic lenses. Optically, various orders of wavefront aberrations are purposely induced by a commercial MEMS (micro-electrical–mechanical systems) DM (deformable mirrors) with 140 actuators. The optical properties of fluidic lenses are characterized by Shack–Hartmann measurements. It is experimentally shown that piston mode (Z1) can be significantly improved from 0.972 μm to −0.031 μm using fluidic lenses by injecting DI water as little as 0.02 ml. Similar improvements can be found in defocus (Z5)/astigmatism (Z6) and aberrations are reduced for both modes from −0.15 μm/−0.48 μm to 0.02 μm/0.085 μm, respectively.

1. Introduction

Stringent image quality yet lighter and compact configuration are the intensive areas of research for contemporary optical devices. In order to fulfill the above-mentioned requirements, fluidic lenses have been proposed that with an adjustable focal length over a wide range and changing the shape of the fluidic lens without any mechanical moving parts [1,2], not only can the lens properties be tuned dynamically but also different lens types [3]. It is also for ophthalmic applications with continuously varying optical powers of second order Zernike modes to correct both myopic and hyperopic defocus [4]. In particular, adjustable fluidic lens with variable and controllable curvatures are demonstrated to exhibit optical powers between −20D and +20D [5] as well as phoroptors of adjustable astigmatic and defocus lenses [6]. Moreover, a tunable polymer lens of solid-state variable focal lens based on shape changes in a mechanically actuated elastomeric membrane is proposed and focal length of a factor of 1.9 is achieved [7]. A zoom ratio higher than 4.0 is achieved by incorporating both telephoto (concave–convex) and reverse-telephoto (convex–concave) into one fluidic adaptive zoom lens system [8]. It is also investigated that a combination of suitable optical liquids with appropriate radii of the liquid's interfaces, diffraction-limited resolution over a wide focal tuning range are theoretically and numerically possible [9]. It is also demonstrated that liquid lenses can be integrated with stimuli-responsive hydrogels [10] and electromagnetic actuators [11,12] to produce functionally complex yet relatively simple optical systems, such as variable-focus liquid lenses for miniature cameras [13]. An adaptive liquid lens actuated by a photo-polymer is demonstrated. The polymer is bent under blue light irradiation, which exerts a pressure to regulate the curvature of the membrane and then change the focal length of the plano-convex lens [14]. Deformable liquid droplets for optical beam control [15] and optical switch with a reconfigurable dielectric liquid droplet [16,17] have potential applications in light shutters, variable optical attenuators, adaptive irises, and displays. Among them, adjustable or tunable fluidic lenses are mainly investigated as either zoom lenses without varying the lens spacing or aberration correctors without mechanically moving lenses. Recently, the induced aberrations were rarely discussed before. We address this issue by first clarifying the aberrations experimentally due to injected fluidic volumes. We consider the aberration introduced by interfaces of RIM between water/oil and glass [18]. However, the lack of a systematic research on

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induced aberrations in terms of Zernike modes and the potentials of adjustable fluidic lens are not fully explored. In this paper, we will focus on aberrations expressed by Zernike polynomials, preferably the first six modes commonly encountered in ophthalmology, to correct wavefront aberrations induced by MEMS (micro-electrical-mechanical systems) DM (deformable mirrors).

2. Fabrication of fluidic lenses

An indispensable component of the fluidic lens is a PDMS (polydimethylsiloxane,) membrane that can be deformed to facilitate the corrections in the optical wavefront. The PDMS (Sylgard 184, Dow Corning) was mixed with a 10:1 ratio to curing agent and then poured into a mould cavity about 10 mm in diameter. The PDMS was then placed in a vacuum for about 30 min to remove excess air bubbles. Next, the membrane was baked in an oven at 65 °C for four hours to completely cure the PDMS [4]. The PDMS membrane was then removed from the mould and measured to be approximately 550 μm thick. Detail construction of adjustable fluidic lens is shown in an explosive view in Fig. 1(a) and fabricated prototype in Fig. 1(b). Three components of aluminium holder is designed to provide mechanical mounting of both PDMS membrane and glass (1 mm thick, Menzel-Glaser, Superfost, refractive index 1.523). The middle portion of the holder consists of a 20 mm diameter circular aperture and 8 mm thick fluidic chamber. One tapped holes for connection to a syringe to provide volumetric changes. The edge of the aperture was bevelled and sealed with two O-ring installations so that the membrane would maintain a minimum amount of tension to avoid unwanted ripples [4–6].

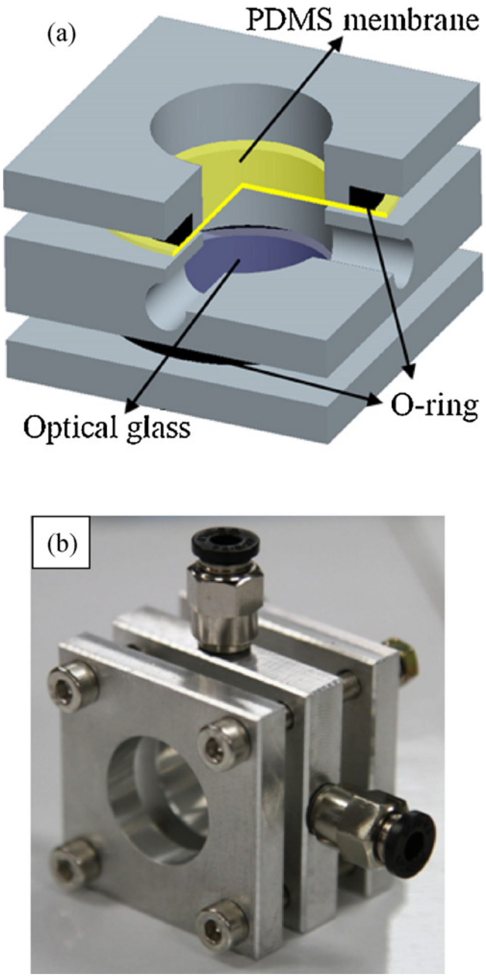

Fig. 1. Schematic for the construction of a fluidic lens. Explosive view shown in (a). The upper plate is shown with the PDMS membrane of 550 μm thick. The holder functions as the mechanical mounting using an optical glass of 1 mm thick. Glass can be replaced by another PDMS membrane and bi-concave or bi-convex configurations can be realized by simultaneously injecting or retracting liquids. Constructed prototype of fluidic lens and optical photo is shown in (b).

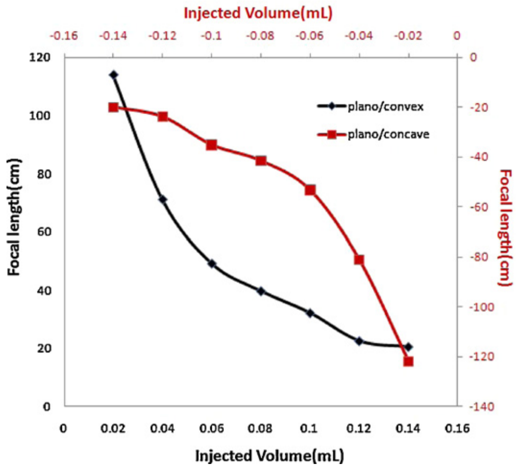

Fig. 2. Measured focal length as a function of the injected volume for both types of fluidic lens.

3. Liquid lens performance

To demonstrate the capability of the fluidic lenses with different focal lengths as well as different lens types such as plano/convex and plano/concave, the measured focal lengths for both convex and concave lens types as a function of the injected volume are firstly presented in Fig. 2. It is noted that the absolute values of the focal length of both types of fluidic lenses cover a wide range – from 20 to about 120 cm. Moreover, the variation of focal length with respect to injected volume is very consistent, which agrees well with the theoretical analysis for the membrane deformations under uniform pressure [19].

It is concluded that the focus can be easily tuned by adjusting the liquid volume. Fig. 3(a) and (b) shows the photographs for the image quality at two different focal lengths of 25 and 700 mm, respectively. Images were recorded with a digital camera. Above focal length tunability can be achieved by simply changing the fluid volume in the liquid lens from 0.04 to 0.6 ml. The focal distance is measured from the center of the meniscus lens to the surface of the digital camera.

4. Optical setup of aberration experiments

A schematic diagram explaining experimental setup is shown in Fig. 4. The aberration generation system used in this research was an MEMS DM with 140 actuators (12 × 12 array and aperture of 4.4 mm × 4.4 mm) from Boston Micromachines Corporation. A Shack–Hartmann wavefront sensor (S–H) form Thorlabs was utilized to measure the wavefront aberrations. The laser beam (diode laser, $\lambda = 635$ nm) is collimated by a pair of lenses (L1 and L2, 100- and 75-mm focal lengths) with a 0.75 magnification factor and two mirrors. The light passed another pair of relay lenses (L3 and L4, 75- and 75-mm focal lengths) and irradiated on DM. The DM typically serves as a correction device with closed-loop control. However, we utilize DM to intentionally produce aberrations of various degrees and later be corrected by fluidic lenses. The laser beam reflected by the DM then passed through one additional pair of lenses (L5 and L6, 75- and 75-mm focal lengths) and the BS (beam splitter) to conjugate the microlens array plane of the S–H and DM plane as