1-1-2006

Tunable-focus liquid lens controlled using a servo motor

Hongwen Ren
University of Central Florida

David Fox
University of Central Florida

P. Andrew Anderson
University of Central Florida

Benjamin Wu
University of Central Florida

Shin-Tson Wu
University of Central Florida

Recommended Citation

Ren, Hongwen; Fox, David; Anderson, P. Andrew; Wu, Benjamin; and Wu, Shin-Tson, "Tunable-focus liquid lens controlled using a servo motor" (2006). *Faculty Bibliography 2000s*. 6496.
https://stars.library.ucf.edu/facultybib2000/6496

Tunable-focus liquid lens controlled using a servo motor

Hongwen Ren, David Fox, P. Andrew Anderson, Benjamin Wu, and Shin-Tson Wu

College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816
swu@mail.ucf.edu

Abstract: We demonstrated a liquid lens whose focal length can be controlled by a servo motor. The lens cell is composed of elastic membrane, planar glass plate, a periphery sealing ring, and a liquid with a fixed volume in the lens chamber. Part of the periphery sealing ring is excavated to form a hollow chamber which functions as a reservoir. This hollowed periphery is surrounded by an exterior rubber membrane. The arm of a servo motor is used to deform the elastic rubber. Squeezing the liquid contained in the reservoir into the lens chamber. Excess liquid in the lens chamber will push the lens membrane to outward, resulting in a lens shape change. Due to the compact structure and easy operation, this liquid lens has potential applications in zoom lenses, auto beam steering, and eyeglasses.

OCIS codes: (010.1080) adaptive optics; (220.3620) lens design; (220.2560) focus

References and links

1. S. Sato, “Liquid-crystal lens-cells with variable focal length,” Jpn. J. Appl. Phys. **18**, 1679-1684 (1979).
2. A. F. Naumov, G. D. Love, M. Yu. Loktev, and F. L. Vladimirov, “Control optimization of spherical modal liquid crystal lenses,” Opt. Express **4**, 344-352(1999).
3. M. Ye and S. Sato, “Optical properties of liquid crystal lens of any size,” Jpn. J. Appl. Phys. **41**, L571-L573 (2002).
4. H. Ren, Y. H Fan, S. Gauza, and S. T. Wu, “Tunable flat liquid crystal spherical lens,” Appl. Phys. Lett. **84**, 4789-4791 (2004).
5. M. Vallet, B. Berge, and L. Vovelle, “Electrowetting of water and aqueous solutions on poly (ethylene terephthalate) insulating films,” Polymer **37**, 2465-2470 (1996).
6. T. Krupenkin, S. Yang, and P. Mach, “Tunable liquid microlens,” Appl. Phys. Lett. **82**, 316-318 (2003).
7. S. Kuiper and B. H. W. Hendriks, “Variable-focus liquid lens for miniature cameras,” Appl. Phys. Lett. **85**, 1128-1130 (2004).
8. G. C. Knollman, J. L. Bellin, and J. L. Weaver, “Variable-focus liquid-filled hydroacoustic lens,” J. Acoust. Soc. Am. **49**, 253-261(1971).
9. N. Sugiura and S. Morita, “Variable-focus liquid-filled optics lens,” Appl. Opt. **32**, 4181-4186 (1993).
10. D. Y. Zhang, V. Lien, Y. Berdichevsky, J. Choi, and Y. H. Lo, “Fluidic adaptive lens with high focal length tunability,” Appl. Phys. Lett. **82**, 3171-3172 (2003).
11. K.-H. Jeong, G. L. Liu, N. Chronis, and L. P. Lee, “Tunable microdoublet lens array,” Opt. Express **12**, 2494-2500 (2004).
12. J. Chen, W. Wang, J. Fang, and K. Varahramyan, “Variable-focusing microlens with microfluidic chip,” J. Micromech. Microeng. **14**, 675-680 (2004).
13. N. Chronis, G. L. Liu, K.-H. Jeong, and L. P. Lee, “Tunable liquid-filled microlens array integrated with microfluidic network,” Opt. Express **11**, 2370-2378 (2003).
14. K. S. Hong, J. Wang, A. Sharonov, D. Chandra, J. Aizenberg and S. Yang, “Tunable microfluidic optical devices with an integrated microlens array,” J. Micromech. Microeng. **16**, 1660-1666 (2006)
15. H. Ren, and S. T. Wu, “Variable-focus liquid lens by changing aperture,” Appl. Phys. Lett. **86**, 211107 (2005).
16. J. Li, G. Baird, Y. H. Lin, H. Ren, and S. T. Wu, “Refractive-index matching between liquid crystals and photopolymers,” J. Soc. Info. Display **13**, 1017-1026 (2005).

1. Introduction

Adaptive lenses are useful for auto beam steering, cell phone cameras, eyeglasses, and other optical signal processing applications. Two mechanisms have been widely employed for

#72635 - $15.00 USD Received 3 July 2006; revised 7 August 2006; accepted 17 August 2006

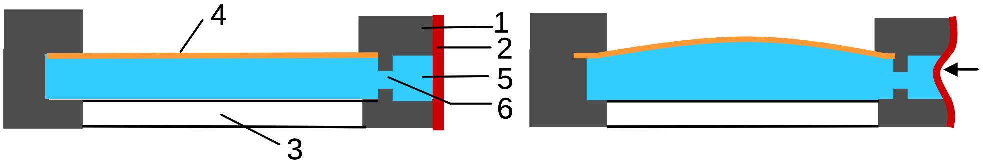
making an adaptive lens: shape change and refractive index change. To mimic a human eye, the shape change leads to a large optical path-length change and therefore a large diopter. Compared with liquid-crystal lenses which focus light based on refractive index change [1-4], adaptive liquid lenses present the highest quality performances [5-14]. Moreover, the liquid lens can exhibit a high lens power at a large aperture size and its focal length can be adjusted at a wide range because of the change of the surface curvature. According to the operation mechanism, liquid lenses can be classified into two types. The first type is the electrowetting lens [5-7]. By applying a voltage the liquid lens can go through continuous focus change and its response time is fast. However, an electrowetting lens requires a relatively high voltage (~100V). Moreover, making a larger aperture electrowetting lens remains a challenging task. The second type is the mechanical lens [8-14]. By pumping liquid in/out of the lens chamber or moving the periphery of the lens forward and backward along the lens axis, the liquid inside the lens chamber is redistributed such that the curvature of the elastic membrane is changed. Both of the liquid lenses can present a high lens power without changing the lens aperture size. However, the operating systems for tuning the focus are complicated.

Recently, we developed a mechanically tunable liquid lens by changing aperture using an iris diaphragm [15]. This kind of lens can be easily fabricated and the focal length can be varied easily. The drawback of this lens is the sacrifice of its aperture for higher focusing power. Moreover, the employment of the iris diaphragm made the lens complicated.

In this paper, we report an adaptive liquid lens whose focal length is controlled using a servo motor. In the lens cell, part of the peripheral sealing ring is excavated to form a hollow cavity. This cavity is covered by a thin rubber membrane and used as a reservoir. To operate the liquid lens, we use a voltage controlled servo motor to deform the exterior rubber membrane and force liquid from the reservoir to the lens chamber. The redistributed liquid pushes on the membrane and forms a lens-shape. In comparison with other liquid lenses, this liquid lens has several advantages such as automatic operation, compact structure, no size limitation, and low cost.

2. Lens structure and operation mechanism

Figure 1 depicts the structure of the liquid lens. The left shows the lens at no focusing state and the right shows the lens at focusing state. It is composed of an annular sealing ring (1), exterior rubber membrane (2), a glass plate (3), an elastic membrane (4), liquid as a reservoir (5), and a channel (6). The outboard of the annular sealing ring is wrapped using an elastic rubber membrane to confine the liquid. The elastic membrane is adhesively sealed on the upper side of the sealing ring and the glass plate is fixed tightly on the bottom side of the sealing ring. When no force is acting on the elastic rubber membrane, the elastic membrane is flat. Thus the liquid lens has no focus effect, as shown in Fig. 1(a).



(a) (b)

Fig. 1. Side view of the liquid lens cell: (a) without and (b) with convex lens profile. 1-annular sealing ring, 2-rubber membrane, 3-glass plate, 4-elastic membrane, 5-liquid, and 6-a hole

When the wrapped rubber membrane is pressed in, as shown in Fig. 1(b), liquid stored in the reservoir is forced into the lens chamber. Assuming the volume of the liquid is not constringent and the glass plate is strictly rigid, the changed volume of the exterior membrane is equal to that of the displaced liquid. Because the elastic membrane is much easier to deform than that of the exterior rubber membrane, liquid is redistributed in lens chamber, causing the

Received 3 July 2006; revised 7 August 2006; accepted 17 August 2006

elastic membrane to swell outward. Under such a circumstance, the cell behaves like a convex lens. The changed curvature of the elastic membrane will change the focal length of the lens. To deform the rubber membrane, a servo system was used as shown in Fig. 2. The position of the liquid lens is fixed. A thin string is used to wrap the exterior elastic rubber. One end of the string is fixed and the other end is tied on the arm of the servo motor. To control the servo, a pulse width modulation scheme was implemented with a digital potentiometer and a bidirectional momentary switch. In the original state the string touching the periphery of the liquid lens gently without squeezing the rubber membrane, therefore the lens has no focusing effect. If a voltage is applied to the servo system and the servo motors stator is rotated counterclockwise, the rubber membrane of the liquid lens is deformed, thus causing a focusing effect.

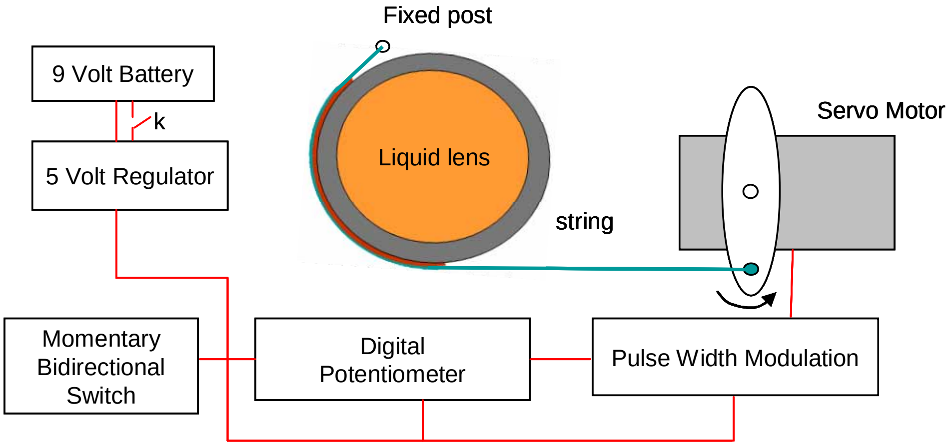


Fig. 2. Structure of a servo system

3. Lens fabrication

To demonstrate our liquid lens, we fabricated an annular sealing ring with a cross-section similar to the structure shown in Fig. 1. The effective aperture of the ring is r=15 mm. The diameter of the periphery ring is ~28 mm. The thickness of the liquid layer in the planar state is 6 mm. A circular glass plate was adhesively sealed tightly on one side of the sealing ring. The opposite side was sealed using a polydimethylsiloxane (PDMS) elastomeric membrane. We chose PDMS as the lens elastic membrane because of its good optical properties with large elongation and bio-compatibility. As a lens material, PDMS is highly transparent (over 96%) in the range of visible wavelength. Its refractive index is n_{PDMS}=1.410. In this research, PDMS membrane was prepared by coating SYLGARD 184 Silicone Elastomer (91 wt% base plus 9% curing agent) on a planar glass substrate. After baking at 150°C for 30 minutes, the membrane was peeled off the glass substrate. The thickness of the PDMS membrane was measured to be ~60 μm. The periphery of the sealing ring was wrapped using transparent rubber membrane. A small hole was drilled on the border of the annular sealing ring (not shown in Fig. 1) to allow a liquid, such as water, to be injected into the lens chamber. After the lens chamber was full, the hole was plugged using a screw.

4. Lens profile and focal length in theory

According to Fig. 1, when the exterior elastic membrane is pushed in, a convex lens profile is formed. Usually, the surface configuration of the liquid lens is alike a paraboloid, as depicted using the solid curve in Fig. 3. If we use a spherical profile (dashed curve) substitute the parabolic-like profile (R is the radius of the spherical curvature) and suppose they have the same maximum displacement *h*, and the same base radius $\mathbf{r_0}$, then the maximum error in displacement can be expressed as [8]:

Received 3 July 2006; revised 7 August 2006; accepted 17 August 2006

$$\Delta z_{\max} < h(h/2r_0)^2 \tag{1}$$

In comparison with the aperture of the lens, if the altitude of the lens satisfies the following condition:

$$h << 2r_0, \tag{2}$$

then the error may be negligible. For example, if a liquid lens has a fixed aperture $2r_o$=15 mm and maximum displacement of h=0.2 mm, then according to Eq. (1), the maximum error in displacement is $\Delta z_{\max}$ <0.036 µm. Such a value is quite small, thus one can apply standard spherical lens equations when dealing with the liquid lens.

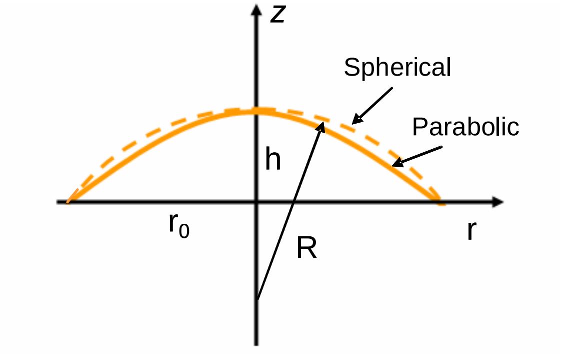


Fig. 3. Approximation of lens profile by a spherical shape.

The operating mechanism of our liquid lens, which works by pressing the exterior membrane, is similar to the pumping-in method. In our lens, when the reservoir is squeezed, the volume change (ΔV) in the effective lens chamber will force the PDMS membrane to bulge outward. The radius of lens curvature (R) and ΔV have the following relationship

$$\Delta V = \frac{1}{3}\pi(2R^2 - r_0^2 - 2R\sqrt{R^2 - r_0^2})(2R + \sqrt{R^2 - r_0^2}) \tag{3}$$

where r_0 is the radius of the lens aperture. If r_0=7.5 mm and the influence of the PDMS film on the liquid lens is negligible, then the relationship of R and ΔV are shown in Fig. 4.

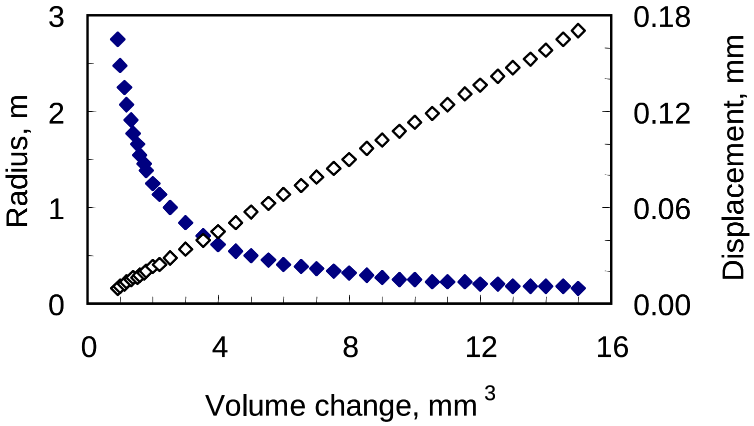


Fig. 4. Volume change versus lens curvature (left) and membrane displacement (right).

Received 3 July 2006; revised 7 August 2006; accepted 17 August 2006

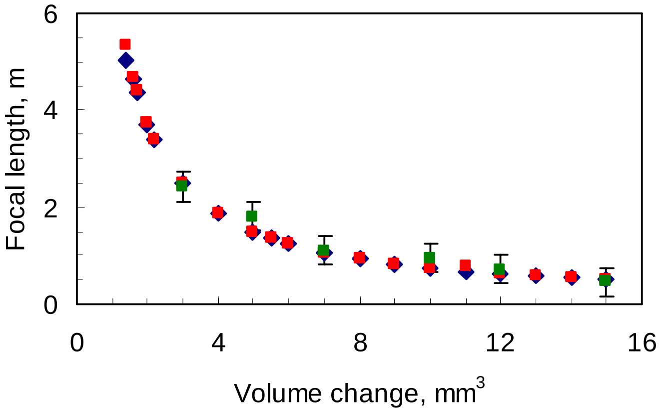


Fig. 5. Focal length versus volume change. Red: thin lens, blue: thick lens, and green: experimental measurement. The black is the error bar.

One can see that as the displaced volume increases the radius of the lens curvature decreases. The variable maximum displacements of the convex lens are also given in Fig. 4. If the safely squeezed volume is 15 mm^3, then the maximum displacement is calculated to be ~0.17 mm. From Eq.(1), the maximum error in displacement is ~0.022 μm. Therefore, we can use the standard spherical lens equation to deal with the liquid lens.

If our liquid lens is considered as a thin lens, then the effective focal length of the lens can be calculated using the following equation:

$$f = \frac{R}{n_{liquid} - 1}, \tag{4}$$

where n_{liquid} is the refractive index of the liquid. To describe the focal property of the lens, the effective focal length of the lens was calculated using Eq. (4). If pure water is used as the lens liquid, according to Fig. 4, the focal length versus the volume change is calculated and the results are shown in Fig. 5 in red color.

As the displaced volume increases, the focal length of the lens has the tendency to be decreased. If we care about all the parameters of the liquid lens, then the lens is not a real thin lens. So we recalculated the effective focal length of liquid lens while considering all of the parameters of the liquid lens using Code-V. The parameters of the lens are the refractive index n_{water} ~1.333, water chromatic dispersion V_d ~64.21, the thickness of water in the planar state d~6 mm, and thickness of glass plate (BK-7) ~0.7 mm. The influence of PDMS on the lens is negligible. The field stop is set right behind the position of glass plate. Using Code-V, one can get two different focal lengths: the effective focal length and the back focal length. The calculated effective focal length is shown in Fig. 5 in blue color. If the changed volume is the same, the thin lens has a little longer focal length than that of the thick lens. However one can see that the data matches well and the small error is negligible. So the liquid lens can be treated as a thin lens.

5. Focal length measurement and lens quality evaluation

To measure the focal length, we expanded and collimated a He-Ne laser beam (λ=633 nm) to ~15 mm in diameter and let it normally pass through the liquid lens. The liquid lens was set in vertical direction. A screen was placed behind the lens for detecting the focal point. The measured focal length versus the volume change of the lens is shown in Fig. 5 in green color. When no liquid is pushed into the lens chamber, the focal length is at infinity. As the

Received 3 July 2006; revised 7 August 2006; accepted 17 August 2006

displaced volume of the water increases, the focal length decreases significantly. From Fig.5, the theoretically calculated results and the experimental measurement results match well.

To evaluate the image quality of our liquid lens under white light environment, we use a resolution target bar as the object. The object was set right behind the lens at ~7 cm. To test the gravity effect of the liquid on the membrane curvature, we intentionally set the lens in vertical direction. A digital camera was fixed right before the liquid lens at ~11 cm. Figure 6 shows two photos of the water lens in (a) planar state and (b) focusing state. In planar state, the PDMS membrane is flat and the observed image through the lens is the same size as the object. By pushing the water into the lens chamber, the image is enlarged. The more water squeezed, the larger image can be observed. Although the lens was set in vertical direction and the lens is a little thick, the observed aberration is not obvious and the enlarged image is highly clear. Visually, we are able to resolve better than 25 lp/mm clearly.

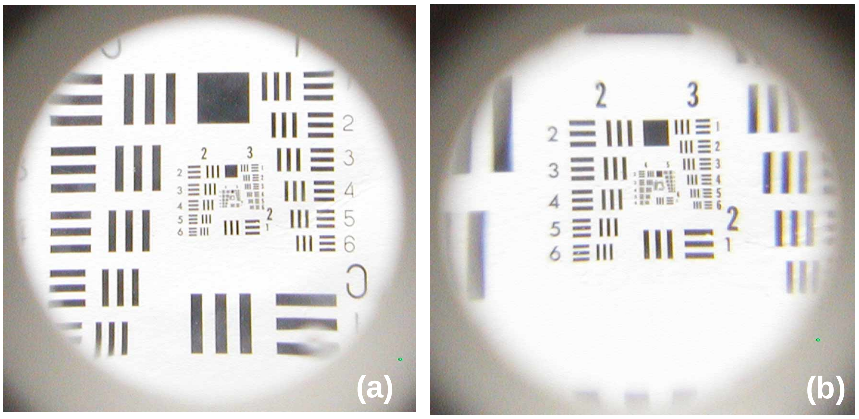


Fig. 6. Focusing behavior of the liquid lens in (a) planar state and (b) focusing state. The aperture of the lens is 15 mm and the lens thickness is 6 mm.

Although we use water for feasibility demonstration, it has two shortcomings: high density and low refractive index. To improve the focusing power of the liquid lens and decrease the lens aberrations caused by gravity, it is better to use a high index liquid but with relatively low density, such as microscope immersion oil (n=1.51), dimethyl silicon oil (n=1.60) or liquid polymer (Norland optical adhesive 81, n_p ~1.56) [16]. To reduce the lens weight and improve the optical quality, we could increase the aperture ratio and decrease the lens thickness. The present liquid lens is operated using a servo motor system which is controlled electrically. For practical applications, the electrically tunable liquid lens would be more attractive for use in cellular phones, cameras, eyeglasses, and other machine visions. The electrically tunable liquid lenses have promising applications.

6. Conclusion

We have demonstrated a tunable-focus liquid lens by shrinking its elastic periphery without changing the aperture. The prototyped lens is a converging lens whose focal length can be tuned continuously by pushing the liquid into its lens chamber. Such a liquid lens is simple to fabricate, easy to operate, compact, and low cost. By choosing a proper electrically-controllable actuator, the liquid lens can be operated electrically rather than mechanically.

Acknowledgments

The authors would like to thank Drs. Haiqing Xianyu, Sebastian Gauza and Ms. Ying Zhou for their technical assistance and useful discussions.

Received 3 July 2006; revised 7 August 2006; accepted 17 August 2006