Adaptive liquid lens actuated by ferrofluid

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ABSTRACT

We present an adaptive liquid lens whose properties are controlled by ferrofluids. The structure is made from acrylic glass and contains two lens chambers separated by an aluminum ring and a channel that connects to both chambers. One chamber is filled with water (glycerol) and the other with a silicone elastomer curing agent, Sylgard 184 (SantoLight Optical Fluids SL-5267). These fluids were chosen because of several key properties; they have comparable densities, they are immiscible with each other, and they have a practical difference between their refractive indexes. The ferrofluid is moved within the channel via an electromagnet and is able to push the liquids into the desired chamber, causing deformation of the membrane curvature. Both divergent and convergent lenses are attainable.

INTRODUCTION

Conventional optical zoom lenses are comprised of several individual lenses and often moving parts that are mechanically driven¹. Such systems are difficult to miniaturize and face problems of actuation in autofocus and zooming functions when the size is reduced^{2, 3}. Adaptive liquid lenses offer high image quality and large optical zoom without the moving parts. Furthermore, the performance of variable liquid lenses has been known to increase when miniaturized². There are several methods that have been developed to control a liquid lens including electro and mechanical-wetting³⁻⁵, hydrogel actuation⁶⁻⁸, the dielectric effect⁹⁻¹², and pressure-based actuation¹³⁻¹⁸.

There are several drawbacks to liquid lenses however, most notably the gravity effect and the relatively short lifetime. The deformations caused by gravity on liquid droplets can be reduced by replacing the surrounding air with an immiscible liquid¹⁹. The short lifetime of liquid lenses is an important obstacle in their applicative capacity which can be attributed to evaporation of materials, blurring at the liquid-liquid interface, micro-bubbles, etc.

The lens presented is actuated by electromagnetically influencing the position of ferrofluid. A ferrofluid is a colloidal mixture containing nanoscale ferromagnetic particles suspended in water or some organic solvent. The

mixture also contains a surfactant in order to prevent agglomeration of the particles. In the presence of a magnetic field the ferrofluid becomes strongly magnetized. However, ferrofluids do not retain magnetization when the external magnetic field is removed Ferrofluids have applications in several fields including electronic devices, mechanical and aerospace engineering, medicine, optics, and even art²⁰.

In these experiments an adaptive liquid lens is demonstrated in which the curvature, and thus the focal length, of the lens is continuously varied through an applied external magnetic field. The lens can become both positive and negative, allowing the desired image to be either magnified or reduced. This is made possible because of the physical relationship between the liquids and the metal disc. Throughout the range of the lens the contact angle between the liquids and the metal disc stays the same. The energy involved (γ) in the equilibrium of a contact angle is illustrated in figure 1(a)²¹. In the case of the liquid lens the energy of the ambient (gas/vapor) is replaced by another liquid. At equilibrium the following equation, known as the Young Equation, is satisfied.

$$0 = \gamma SV - \gamma SL - \gamma \cos \theta c$$

In the equation above²¹ γ SV represents the solid-vapor interfacial energy, γ SL the solid-liquid interfacial energy, γ the liquid-vapor energy, and θ c the contact angle.

However, natural deviations from this equation can arise due to several imperfections including nonconformity in surface smoothness or chemical composition, resulting in contact angle hysteresis. The hysteresis is the difference between what is referred to as the advancing and receding angles which are demonstrated in figure $1(b)^{22}$. The advancing angle is the maximum stable angle and the receding angle is the minimum stable angle that exists between the liquid and solid. Using the advancing and receding angles, the contact angle can be more accurately calculated²³.



Figure 1 (a) illustrates the equilibrium between three phases, a solid substrate, a liquid, and a gas, and the resulting contact angle. Figure 1 (b) illustrates the advancing angle and receding level which are used in the calculation of the contact angle hysteresis.

DEVICE STRUCTURE DEVELOPMENT

Figure 2(a) shows the first lens chamber design. The structure is cylindrical with the channel for the ferrofluid running height-wise along the inside of the assembly. The channel was placed as close as possible to the outside wall of the structure in order to minimize the distance between the magnet and the ferrofluid and the amount of interference from the plastic. The larger chamber was filled with water and the smaller with Sylgard 184. The two liquids meet in the center of an aluminum disc (diameter 3 mm) placed between the chambers. Figure 2(b) retains the cylindrical chambers but the entire structure is rectangular, allowing for a longer channel that runs diagonally. The same difficulty arose in both structures; a bubble was difficult to prevent from forming at the upper edge of the chamber when filling it with water. To simplify the filling process figure 2(c) features a cone shaped chamber whose radius is the same as the aperture radius (the radius of the center of the aluminum disc). The last structure in figure 2(d) was designed for demonstration purposes. It uses rubber tubing in order to connect a capillary tube, used as the ferrofluid channel, to the liquid chambers. The capillary tube offers a longer channel than the other structures but is not as compact, making it only applicable for theoretical demonstration.



Figure 2 (a) Original cylindrical lens chamber, (b) lens chamber with increased channel length for ferrofluid, (c) improved design to eliminate the formation of a bubble, (d) chamber for the purpose of demonstration.

Materials

There were two sets of liquids used in the construction of the lens; Water ($n_1 = 1.33$) and Sylgard 184 ($n_2 = 1.40$ and specific gravity @ 25°C 1.03) and glycerol and SantoLight Optical Fluids SL-5267. Some of the physical properties of glycerol and the optical fluid are shown in Table I. Although the difference in refractive index between the glycerol and optical fluid is markedly higher than the water and Sylgard, the higher densities of the former materials necessitates more force to be applied by the ferrofluid and would undoubtedly yield a higher response time than the water and Sylgard lens. The ferrofluid used in the experiments is characterized in Table II. During operation the ferrofluid piston occasionally separates from itself while traveling through the channel. A denser and more viscous ferrofluid could potentially eliminate this occurrence. However, if the ferrofluid is too viscous it either remains stationary or moves too slowly for an effective response time. The more viscous ferrofluids could potentially be used in a larger channel.

Table I
Physical properties of glycerol and optical fluid

	Refractive Index at $\lambda = 550 \text{ nm}$	Refractive Index at $\lambda = 1293 \text{ nm}$	Refractive Index at $\lambda = 1310 \text{ nm}$	Surface Tension (mN/m@20°C)	Density p (g/cm ³)
Glycerol	1.474	1.460	_	64	1.25
SantoLight Optical Fluid SL-5267	1.670	_	1.635	50	1.26

Table IIPhysical properties of the ferrofluid used

Densi	ty	Viscosity	Surface tension	Volatility	Nominal particle diameter	Saturation magnetization	
1.21 g/	ml	6 cp@27°C	29 dynes/cm	9% (1 hr.@50°C)	10nm	400 Gauss	

Oxygen plasma treatment

We attempted to create a metal disc with a hydrophilic and a hydrophobic side in order to strongly enforce the aperture area. One of the discrepancies that surfaced in the experiments was that instead of inverting from positive to negative, the lens curvature would remain positive and descend into the bottom chamber as depicted in figure 3. Although the image could be magnified by exaggerating the curvature in the positive direction, the image could not be reduced.

Teflon was to be applied on one side of disc to induce a hydrophobic character. To obtain hydrophilicity on the other side, the metal disc was treated with oxygen plasma with the FEI 200 TEM (Transmission Electron Microscopy) FIB (Focused Ion Beam) Instrument. The following two chemical reactions govern the plasma etching process.

O_2	+	O^+	\rightarrow	O_2^+	+	0	(1)
O_2^+	+	e ⁻	\rightarrow	0	+	0	(2)

The process is most often used for cleaning surfaces by allowing oxygen plasma to react with hydrocarbon residues. Another use for the oxygen plasma is to bond PDMS (polydimethylsiloxane) to substrates such as glass, silicone, and PDMS in a condensation reaction²⁴. The treatment has also been told to create a hydrophilic surface on the material exposed, which was the goal in this case. The surface appeared to be hydrophilic after treatment as indicated by the small contact angle when a water droplet was applied. However, once the Sylgard came into contact with the metal ring it was perceptibly hydrophobic. This transition could be attributed to the condensation reaction that occurs with PDMS and silicone based elements. The treatment caused the opposite of the desired effect.



Figure 3 (a) Positive magnifying lens, (b) ideal negative reducing lens, (c) observed progression of the positive lens into the bottom chamber.

RESULTS AND DISCUSSION

An effective lens was constructed and demonstrated in which the curvature of the lens was continuously varied between divergent and convergent. The magnifying ability of the lens is demonstrated in figure 4.



Figure 4 illustrates the magnifying capabilities of the liquid lens actuated by ferrofluid. The pictures are still screen shots from a video that captured the functioning lens. The design of the lens can be seen in figure 2 (c).

To measure the response time of the lens an He-Ne (λ ~633 nm) laser beam was collimated and expanded and passed through the lens. The resulting light was detected and its intensity variation measured by a large area visible photo-receiver (Model 2031, New Focus) connected to an oscilloscope (TDS 3032B, Tektronix). A response time of 2.408 ms and 2.414 ms was measured



for a focusing lens and defocusing lens respectively, as illustrated in figure 5. The data was collected over a back focal distance range of 250 cm to 8 cm.

Figure 5 is the data obtained for the response time of the (a) focusing lens and (b) defocusing lens.

To measure the resolving power of the lens a standard USAF resolution test pattern was used. Figure 6 depicts the resolving power of the lens whose limit was determined to be group 7, element 6 which corresponds to \sim 228 lp/mm.



Figure 6 depicts the resolution of the lens using a USAF resolution test under 50X magnification.

The practical limit to the size of the lens was determined to be approximately 3 mm. As the lens diameter decreases, the back focal distance also decreases, corresponding to an increase in the required traveling distance of the ferrofluid. Figure 7 displays the simulated data that exhibits this occurrence.



Figure 7 (a) Relationship between lens radius (mm) and back focal distance (mm), (b) relationship between ferrofluid displacement (mm) and back focal distance (mm).

CONCLUSIONS

We have demonstrated a liquid lens that is effectively actuated through the use of ferrofluids. The curvature of the lens is continuously altered between a magnifying and reducing state. The lens achieves a fast response time of ~2.4 ms and a high resolution of ~228 lp/mm while offering strong optical power. It can be compacted to a practical diameter of 3 mm. Such a device could be utilized in a wide variety of video-containing electronics.

ACKNOWLEDGEMENT

I would like to thank the following graduate students for their continuous help throughout the summer: Hui-Chuan Cheng, Su Xu, and Yifan Liu.

REFERENCES

- 1. "Zoom Lens." *Wikipedia, the Free Encyclopedia*. Web. 20 July 2010. http://en.wikipedia.org/wiki/Zoom_lens>.
- 2. S. Kuiper and B. H. W. Hendriks, "Variable-focus liquid lens for miniature cameras," Applied Physics Letters **85**, 1128 (2004)
- 3. B. Berge, "Liquid lens technology: principle of electrowetting based lenses and applications to imaging," IEEE conference on Micro Electro Mechanical Systems MEMS 18, 227 (2005)
- 4. S. Grilli, L. Miccio, V. Vespini, A. Finizio, S. De Nicola, and P. Ferraro, "Liquid microlens array activated by selective electrowetting on lithium niobate substrates," Opt. Express **16**, 8084 (2008)
- 5. S. Xu, Y. Liu, H. Ren, and S. T. Wu, "A novel adaptive mechanical-wetting lens for visible and near infrared imaging," Opt. Express **18**, 12430 (2010)
- D. Zhu, C. Li, X. Zeng, and H. Jiang, "Tunable-focus microlens array on curved surfaces," Appl. Phys. Lett. 96, 081111 (2010)
- 7. X. Zeng, H. Jiang, "Tunable liquid microlens actuated by infrared light-responsive hydrogel," Appl. Phys. Lett. **93**, 151101 (2008)
- 8. L. Dong, A. K. Agarwal, D. J. Beebe, H. Jiang, "Adaptive liquid microlens activated by stimuliresponsive hydrogels," Nature **442**, 551 (2006)
- 9. C. C. Cheng and J. A. Yeh, "Dielectrically actuated liquid lens," Optics Express 15, 7140 (2007)
- H. Ren and S. T. Wu, "Tunable-focus liquid microlens array using dielectrophoretic effect," Opt. Express 16, 2646 (2008)
- H. Ren, H. Xianyu, S. Xu, and S. T. Wu, "Adaptive dielectric liquid lens," Opt. Express 16, 14954 (2008)
- S. Xu, Y. J. Lin, and S. T. Wu, "Dielectric liquid microlens with well-shaped electrode," Opt. Express 17, 10499 (2009)
- 13. H. Ren, D. Fox, P. A. Anderson, B. Wu, S. T. Wu, "Tunable-focus liquid lens controlled using a servo motor," Opt. Express 14, 8031 (2006)
- 14. 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 (2003)
- R. Kuwano, T. Tokunaga, Y. Otani, and N. Umeda, "Liquid pressure varifocus lens," Opt. Review 12, 405 (2005)
- 16. H. Ren and S. T. Wu, "Variable-focus liquid lens," Opt. Express 15, 5931 (2007)
- 17. F. Schneider, C. Müller, and U. Wallrabe, "A low cost adaptive silicone membrane lens," Journal of Optics A: Pure and Applied Optics **10**, 044002 (2008)
- H. M. Son, M. Y. Kim, and Y. J. Lee, "Tunable-focus liquid lens system controlled by agnostic winding type SMA actuator," Opt. Express 17, 14339 (2009)
- H. Ren, S. Xu, S. T. Wu, "Effects of gravity on the shape of liquid droplets," Optics Communications 283, 3255 (2010)
- 20. "Ferrofluid." *Wikipedia, the Free Encyclopedia*. Web. 15 July 2010. http://en.wikipedia.org/wiki/Ferrofluid>.
- 21. "Contact Angle." *Wikipedia, the Free Encyclopedia*. Web. 24 July 2010. ">http://en.wikipedia.org/wi
- 22. "Wetting." *Wikipedia, the Free Encyclopedia*. Web. 24 July 2010. http://en.wikipedia.org/wiki/Wetting>.
- 23. R. Tadmor, "Line energy and the relationship between advancing, receding, and Young contact angles," Langmuir **20**, 7659 (2004)
- 24. Jack Rundel, "Plasma etcher: theory of plasma etching," Google <classes.engr.oregonstate.edu>