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Adaptive mechanical-wetting lens actuated by ferrofluids

Hui-Chuan Cheng, Su Xu, Yifan Liu, Shoshana Levi, Shin-Tson Wu *

A R T I C L E I N F O

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A B S T R A C T

We report an adaptive mechanical-wetting lens actuated by ferrofluids. The ferrofluids works like a piston to pump liquids in and out from the lens chamber, which in turn reshapes the lens curvature and changes the focal length. Both positive and negative lenses are demonstrated experimentally. The ferrofluid-actuated mechanical-wetting lens exhibits some attractive features, such as high resolution, fast response time, low power consumption, simple structure and electronic control, weak gravity effect, and low cost. Its potential applications in medical imaging, surveillance, and commercial electronics are foreseeable.

1. Introduction

A conventional zoom lens is comprised of two lens groups separated by a distance. By adjusting the lens separation, zooming effect can be achieved. It offers good resolution, but the whole module is usually heavy and bulky. Adaptive liquid lens is attractive because it combines the functions of several lenses into a single lens. As a result, it is compact and lightweight. More importantly, it eliminates the undesirable mechanical moving parts, so that the assembly process is greatly simplified.

Several types of adaptive liquid lenses have been developed, such as fluidic lens [1–3], membrane liquid lens [4], electro-wetting lens [5], dielectrophoretic lens [6–9], hydrogels activated microlenses [10], and mechanical-wetting lens [11]. As compared to other liquid lenses, mechanical-wetting lens exhibits high resolution, wide dynamic range, and less gravity effect [12]. However, the actuation method for mechanical-wetting lens remains to be developed. Some pressure-based actuators could be applied, such as voice coil motor [13], piezoelectric actuators [14], external pumps [15], shape memory alloy actuators [16], and artificial muscles [17]. However, these methods are usually bulky and inconvenient for practical applications.

By imitating a syringe [18], ferrofluid has been proposed to replace the rubber piston inside the syringe for actuating a liquid lens [19]. Ferrofluid exhibits a much weaker friction than traditional piston when moving inside a syringe. As a result, a smaller pumping force is needed. Moreover, the position of ferrofluids can be electrically controlled by an electromagnet. Ferrofluids are comprised of nanoscale ferromagnetic particles that are suspended in a carrier fluid, e.g., organic solvent or water. They exhibit paramagnetism because of the large magnetic susceptibility; however, the magnetization does not retain when the external field is removed.

In this paper, we demonstrate a mechanical-wetting lens actuated by a ferrofluidic piston. The lens curvature, and thus the focal length, is variable by controlling the external magnetic field through voltage. Our ferrofluids-actuated mechanical-wetting lens exhibits following attractive features: high resolution (~200 lp/mm), fast response time (~2.5 ms), low power consumption, simple structure, easy fabrication, weak gravity effect, and low cost.

2. Device structure

Fig. 1 shows the device structure of our mechanical wetting lens. The lens was made of acrylic glass and comprised of two lens chambers separated by an aluminum ring. Two immiscible liquids were filled in the chambers: water ($n = 1.33$) and Sylgard 184 ($n = 1.40$ and specific gravity $= 1.03$ @ 25 °C). We chose the fluids with matched density in order to minimize the gravity effect. To achieve a good circular lens aperture and shape, we placed an aluminum ring (3 mm in diameter and 0.8 mm in thickness) between two adjacent chambers. The aluminum ring was well polished to have a smooth and homogeneous surface in order to reduce the contact angle hysteresis. The immiscible liquids (water and Sylgard 184) formed an interface in the center of the aluminum ring.

As Fig. 1 depicts, a channel with 1-mm inner diameter connects the lens chambers. The channel was placed near the outside surface of the structure to minimize the distance between the electromagnet (E-66-38, MSS Corp.) and the ferrofluids. A small segment of ferrofluids (~5 mm in length) was injected into the channel which functions as a piston. We also coated polytetrafluoroethylene (i.e., Teflon) inside the channel to prevent ferrofluids from sticking on the inner surface. Because the oil-based ferrofluids would react with Sylgard, we isolated ferrofluids from Sylgard by another segment of water. A pair of electromagnets was used to control the position of ferrofluids.

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* Corresponding author. Tel.: +1 407 823 4763; fax: +1 407 823 6880.
E-mail address: swu@mail.ucf.edu (S.-T. Wu).

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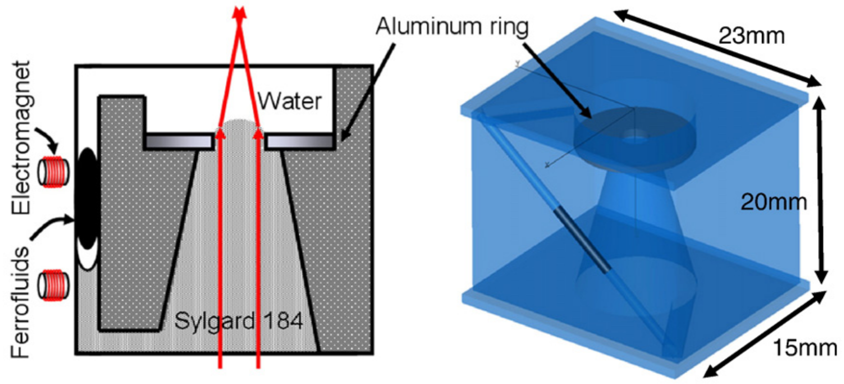

Fig. 1. Device structure of the mechanical-wetting lens.

The physical properties of the ferrofluids we employed (EFH1, Ferrotec Corp.) are listed as follows: density ~1.21 g/ml, viscosity ~6 cP at 27 °C, surface tension ~29 dyn/cm, volatility ~9% (1 h @ 50 °C), and nominal particle diameter ~10 nm. In order to get the piston-like property, ferrofluids with a high surface tension is preferred because high surface tension prevents ferrofluids from sticking on the inner surface of the channel. In addition, if the ferrofluids is too viscous it will have a large friction, leading to a slow response time. We chose the light hydrocarbon oil as the carrier liquid for the ferrofluids because of its negligible solubility in the water.

3. Experiment

Fig. 2(a)–(c) shows the magnifying ability of the mechanical-wetting lens. When the external magnetic field was turned on, the ferrofluids were actuated to move within the channel, which deforms the curvature of the water-Sylgard interface (Fig. 1). Due to the refractive index difference between water and Sylgard 184, both divergent and convergent lenses are attainable. Fig. 2(d) shows the image of a 1951 USAF resolution target taken in the transmissive mode thru an optical microscope with a monochromatic light ($\lambda = 546$ nm). The highest resolution of the device is ~203 lp/mm as the patterns of group 7 number 5 are still resolvable. If we use a white light source, the chromatic aberration will undoubtedly degrade the image resolution.

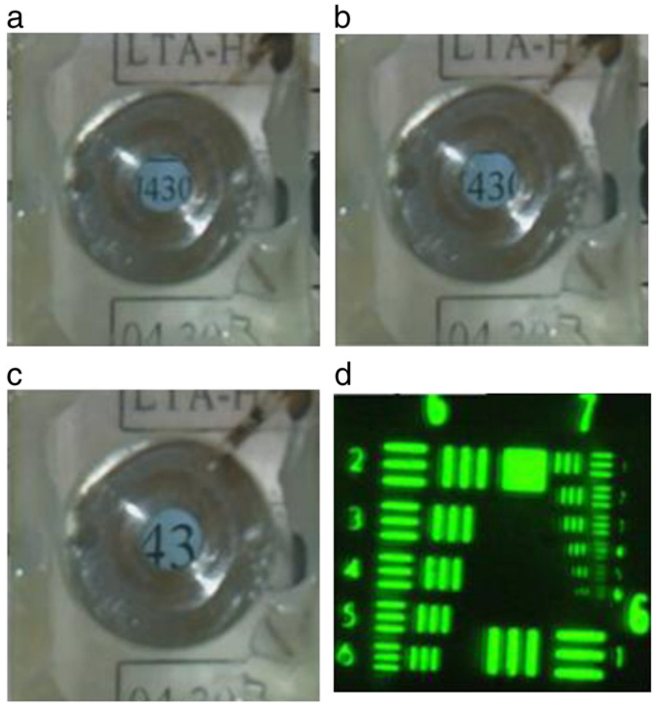

Fig. 2. (a)–(c) Images taken through the negative state to positive state, and (d) resolution test.

Fig. 3 shows the experimental setup for measuring the response time of our mechanical-wetting lens. Without voltage, the lens is in the initial state, like a parallel plate with zero optical power. Therefore, the iris in front of the detector blocks most of the collimated laser beams. As soon as the voltage is applied, the electromagnet-induced magnetic field attracts the ferrofluids. The piston-like ferrofluids push the liquids in the lens chambers to move which deforms the water-Sylgard interface and focuses the laser beam through the iris. We measure the variation of the light intensity after the iris to determine the lens' response time.

Fig. 4(a) and (b) shows the measured response time between a focused state and a defocused state. In Fig. 4(a), the rise time stands for the time of back focal distance (BFD) changing from BFD = 250 cm to 8 cm. In Fig. 4(b), the fall time represents the time for defocusing from BFD = 8 cm to 250 cm. The measured rise time is 2.4 ms and decay time is also 2.4 ms. Such a fast response time is attributed to the low viscosity liquids employed. To further improve response time, we could reduce the lens aperture because it would take a shorter time for ferrofluidic piston to push a smaller amount of liquids. By using a pair of electromagnets to move the ferrofluids forward or backward, the lens could be continuously tunable through an applied external magnetic field.

4. Results and discussions

Fig. 5 simulates the moving distance of ferrofluids versus the corresponding BFD. For the mechanical-wetting lens with 3-mm diameter, the ferrofluids need to move 2.14 mm in order to change BFD from 2500 mm to 50 mm. However, to get BFD shorter than 50 mm, the required moving distance of ferrofluids increases exponentially. It is unfavorable since the longer travel distance corresponds to a slower response time and demands a larger electromagnet. Therefore, the

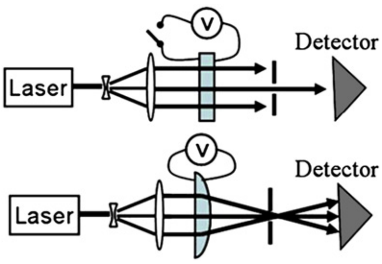

Fig. 3. Experimental setup for measuring the lens response time.

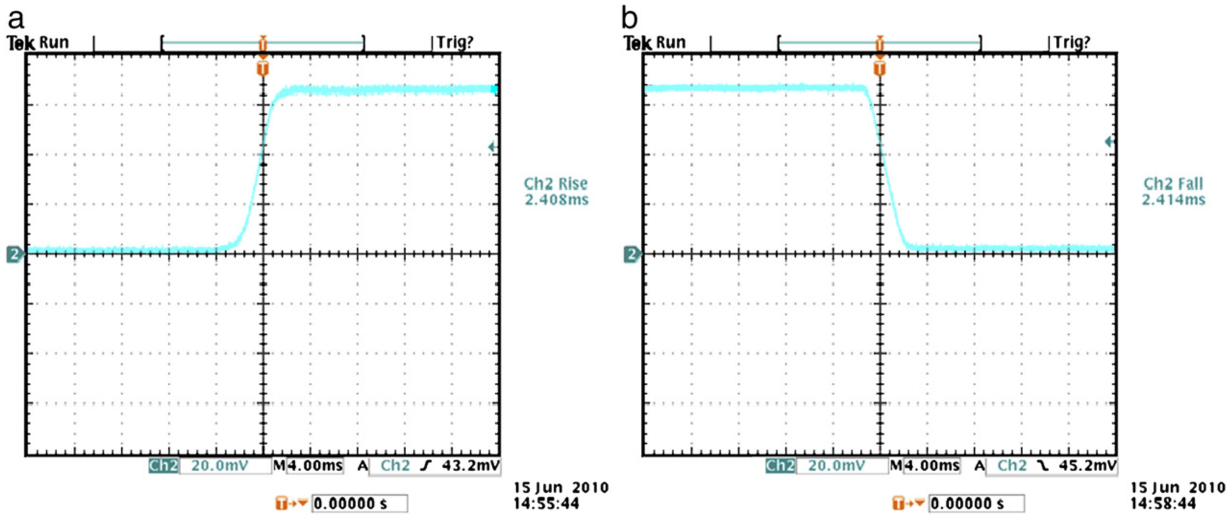

Fig. 4. Measured response time of (a) focusing state, and (b) defocusing state.

practical shortest BFD is ~50 mm for our mechanical-wetting lens with 3-mm diameter.

Fig. 6 shows the relation between lens radius and BFD variation under the same ferrofluids displacement. We assume that the initial focal length is infinity. While the ferrofluids moves 2 mm, the back focal point changes from infinity to ~50 mm for 1.5-mm lens radius. If we want to obtain a shorter BFD, we could reduce the lens radius. Although the minimum BFD would decrease if we keep decreasing the lens radius, the BFD tends to saturate eventually. Besides, a small aperture tends to degrade the image quality. Therefore, a proper balance between wide dynamic range and lens radius should be taken into consideration.

Another method to shorten BFD is to use two immiscible liquids with a larger refractive index difference. Glycerol ($n=1.474$, density $=1.25$ g/cm^3) and SantoLight optical fluid SL-5267 ($n=1.670$, density $=1.2$ g/cm^3) can also be used for our mechanical-wetting lens because of their large refractive index difference and matched density. However, these two liquids are more viscous than water and Sylgard. Consequently, a larger force is needed for actuating the ferrofluids which leads to a slower response time.

As compared to other kinds of liquid lens, our mechanical-wetting lens has several advantages. Selecting immiscible liquids with matched density helps to minimize gravity effect and vibration influence. Because all liquids are sealed in the lens chambers, the mechanical-wetting lens has good stability without volatility issue.

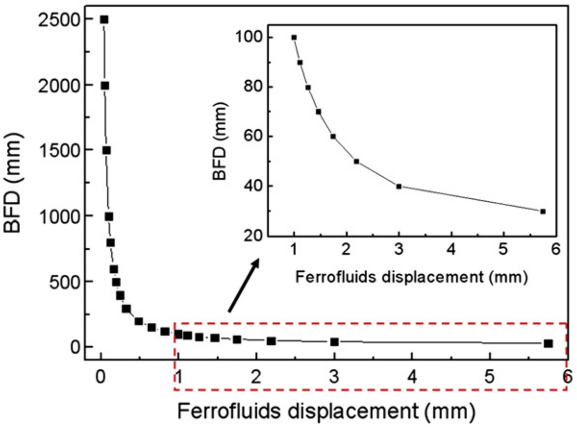

Fig. 5. Relation between ferrofluids displacement and BFD.

As the lens curvature is changed by the moving ferrofluids, we can turn off the applied voltage and the lens curvature will retain the same. Thus, power consumption is minimized because the time with voltage on is very short (approximately the same as response time). This approach is helpful to reduce power consumption and to have more time for releasing the unwanted heat from electromagnet. In our experiment, the input power applied to electromagnets is ~2.4 W which produces 570-Gauss magnetic field intensity.

5. Conclusion

We have demonstrated a new method for actuating mechanical-wetting lens by using ferrofluids. With the control of electromagnets, the ferrofluids pump liquids into lens chambers to alter the lens shape. Both diverging and converging lenses are attainable in our design. From our studies, ferrofluids provide a good solution to actuate mechanical-wetting lens because of its reduced gravity effect, non-volatility, high resolution, fast response time, low power consumption, and simple structure. Such an adaptive lens has promising applications in medical imaging, surveillance devices, and commercial electronics.

Acknowledgments

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Fig. 6. Variation of BFD for different lens radius.

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