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Challenges of using dielectric elastomer actuators to tune liquid lens

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ABSTRACT

Recently, dielectric elastomer actuators (DEAs) have been adopted to tune liquid membrane lens, just like ciliary muscles do to the lens in human eye. However, it faces some challenges, such as high stress, membrane puncture, high driving voltage requirement, and limited focus distance (not more than 707cm), that limit its practical use. The design problem gets more complex as the liquid lens shares the same elastomeric membrane as the DEA. To address these challenges, we separate DEA from the lens membrane. Instead, a liquid-immersed DEA, which is safe from terminal failure, is used as a diaphragm pump to inflate or deflate the liquid lens by hydraulic pressure. This opens up the possibility that the DEA can be thinned down and stacked up to reduce the driving voltage, independent of the lens membrane thickness. Preliminary study showed that our 8-mm-diameter tunable lens can focus objects in the range of 15cm to 50cm with a small driving voltage of 1.8kV. Further miniaturization of DEA could achieve a driving voltage less than 1kV.

1. INTRODUCTION

Hard lens has a fixed focal length and needs motorized translation for auto-focus. In contrast, a crystalline lens in a human eye has a variable focal length under stimulation by ciliary muscles. The natural tunable lens is a lot more compact than the hard lens system to perform focusing task. This inspired development of deformable lens, which consists of membrane enclosure of liquids, albeit tunable by electromechanical means. Various actuation principles have been used to deform the liquid lens, namely mechanical [1], electromagnetic[2], and pneumatic ones. Such focus tunability is very attractive for use to auto focus imaging system in the endoscope or mobile phones. However, conventional eletromechanical actuators, such as servo motor are generally bulky and defeat the purpose of having compact tunable lens design. Recently, dielectric elastomer actuators (DEA), which are very compact and lightweight, has been integrated with the liquid lens, and they can tune the lens just like ciliary muscles do to the eye's lens [3][4]. These bio-inspired tunable lenses could have an aperture as large as the crystalline lens of human eyes but weigh much less than the typical servo motors. They have been demonstrated to focus between near and far objects, which are located at a range between 16cm and 770 cm from the lens[4]. Such wide tuning range is attributed to large actuation strain in the DEA, which was highly pre-stretched and subjected to high Maxwell stress.

Despite its good performance, DEA-tune liquid lens is not without weakness. It faces some challenges, such as high stress, membrane puncture, high driving voltage requirement, and limited focus distance (not more than 707cm), that limit its practical use. One of the major weaknesses is that the DEA requires a very high driving voltage, in the order of several kilovolts. For example, an annular DEA requires a high driving voltage close to 4kV in order to change focus of a 7.6 mm diameter liquid lens, from near to far. This indeed limits the practical use of the DEA for optical tuning. For practical use, the driving voltage for DEA must be less than or equal to 1kV. Ideally, thinning down the DEA could help lower the driving voltage. However, the current design may have the lens aperture miniaturized together with the integrated DEA and adversely has the lens membrane stiffened. As such, the previously developed miniaturized DEAs indeed required more than 1kV driving voltage to tune a 1-3 mm diameter membrane-liquid lens[5]. Furthermore, the DEA are not as durable as the natural ciliary muscles, which lasts long until aging. DEA as a soft deformable under activation by high Maxwell stress is prone to electrical breakdown or mechanical rupture. Though integrity of the DEA-tune lens under high field was not systematically studied, it is expected to be similar to that encountered by the DEA

itself. Miniaturization is expected to compromise the DEA strength because the effect of defects is more pronounced to a thinner elastomeric membrane.

To address these challenges, we separate DEA from the lens membrane. Instead, a liquid-immersed DEA, which is safe from terminal failure, is used as a diaphragm pump to inflate or deflate the liquid lens by hydraulic pressure. This opens up the possibility that the DEA can be thinned down and stacked up to reduce the driving voltage, independent of the lens membrane thickness.

2. PRINCIPLES OF TUNABLE LIQUID LENS USING DEA

A typical tunable lens has liquid medium enclosed by deformable membranes. The liquid is pressurized so that the lens membrane bulges out with an initial curvature when not activated. Dielectric elastomer actuators were used to stimulate curvature change to the tunable lens. There are two types of integrated DEAs for the tunable lens. The first type has an annular DEA radially stretching a tunable lens at the center. Activation of the annular actuator indirectly causes a stress reduction in the lens membrane. The second type has the DEA integrated on the lens membrane and could directly reduces the stress in the lens membrane.

Figure 1. Tunable liquid lens using two types of DEA: (a) annular DEA surrounding the lens, (b) integrated DEA in the lens membrane

Here, a simple model is developed to estimate the tuning behavior of the second type of tunable lens, which has DEA directly integrated in the lens membrane. This tunable lens has a membrane with thickness t enclosing the pressurized liquid. The internal liquid pressure P is balanced by equal biaxial stress σ in the membrane, causing the membrane bulge at a radius of curvature R .

According to the theory for thin-walled pressure vessels[6], the lens curvature follows:

$$\frac{1}{R} = \frac{P}{2t\sigma}.$$

Given a constant pressure and an initial pre-stress, the initial curvature is determined as:

$$\frac{1}{R_0} = \frac{P}{2t\sigma_0},$$

in which σ_0 is the membrane biaxial pre-stress which balances with the initial internal liquid pressure. The pre-stress could be higher if the membrane is pre-stretched initially.

Activation of the integrated DEA reduces the stress in the lens membrane:

$$\sigma'(E) = \sigma_0 - \varepsilon_r \varepsilon_0 E^2,$$

in which the second term is the Maxwell stress induced at the electric field E across the dielectric membrane, with ε_r being the relative dielectric constant for the membrane, and ε_0 being the air permittivity

As result, the activated curvature becomes:

$$\frac{1}{R'} = \frac{P}{2t(\sigma_0 - \varepsilon_r \varepsilon_0 E^2)}.$$

Tuning range lies between the initial curvature and the maximum curvature achievable by electric field activation. When idle, the tunable lens focuses far. When activated, its focus becomes nearer to the lens.

3. CHALLENGES TO TUNABLE LIQUID LENS USING DEA

To maximize the tuning range, one would simply increase the Maxwell stress as much as the initial membrane pre-stress. Yet, it is limited by the maximum Maxwell stress that the dielectric elastomeric membrane can sustain before a breakdown. In addition, the lens membrane under high Maxwell stress is susceptible to puncture at the spot of electrical breakdown. Figure 2 shows that the integrated annular DEA breaks down at very high field, causing radial wrinkles and puncture surrounding the pupil of the tunable lens. As the lens is sharing the same membrane with the integrated actuator, any puncture on the lens membrane immediately led to liquid leakage, which consequently deflates the bulged lens.

The same membrane acrylic elastomer was used to make both the lens and the actuator. It makes simple fabrication. However, sharing of the same elastomeric membrane limits independent design optimization of the optical and the actuator performance. A good actuator design requires the acrylic elastomer be highly pre-stretched. Yet, the high-pre-stretched acrylic elastomer could sometimes be cloudy and not homogenous for optical transmission. On the other hand, stacking of multiple thinner dielectric elastomer membranes is good for lowering the driving voltage to the actuator but it is bad to the lens.

Furthermore, stability is also an issue to the tunable liquid lens. As the elastomeric membrane that encloses the liquid is made of acrylate elastomer, it is subjected to intrinsic viscoelastic behavior. Activation by high voltage is supposed to control the membrane stress. However, it difficult to stably control the membrane stress because the membrane stress relaxes gradually even under a constant control voltage. This adversely affects the shape stability of the lens to stay focused at a fixed distance. Feedback control is therefore required to keep focusing on a target object.

Figure 2. Failure modes of tunable liquid lens with integrated DEA: (left) no failure; (right) failure at very high electric field

4. TUNABLE LENS USING A DEA PUMP

To address these challenges, we separate DEA from the lens membrane. Instead, the liquid lens is tuned by hydraulic pumping with a liquid-immersed diaphragm DEA. Oil immersion over the compliant electrodes was shown to help DEA prevent from premature and terminal failure, which troubled the normal DEA. Separating the lens and actuator allows more choice of lens membrane material, be it optical clear or more stretchable for large curvature change. In addition, it allows the electro-active elastomer be thinned down and multiplied independently of the lens membrane.

Figure 3 shows our proposed tunable liquid lens with a DEA diaphragm pump. The DEA diaphragm separates two hydraulic chambers, which filled completely with oil. Complete oil immersion is expected to ensure the DEA a long lifetime and high dielectric strength [7]. Activation causes the dielectric elastomer diaphragm to bulge away from or towards the hydraulic chamber that is connected to the lens enclosure. In this way, the internal pressure inside the lens enclosure is changed to cause shape change. As the hydraulic chamber has a larger volume as compared to the lens enclosure, small deformation in the electro-active membrane will cause a larger deformation in the lens membrane. This hydraulic amplification could enable a larger curvature change. Besides deflating the lens, it is also possible to inflate the lens if the hydraulic chamber is properly designed, as shown in Figure 4.

Figure 3 Tunable liquid lens with DEA pump

Figure 4 Hydraulic pumping to inflate or deflate the liquid lens

Figure 5 shows a prototype of tunable liquid lens of 8mm diameter, which acts like a magnifying glass when rest idle on top of a grid paper. A preliminary testing showed that the tunable liquid lens with a DEA pump worked. It demonstrated tunable focus on the objects at a distance between 15 cm to 50 cm, respectively, as shown in Figure 6. This prototype requires a maximum driving voltage of 1.8kV to achieve far focus (at 50cm). Comparison with the previous works showed that the driving voltage to achieve the tuning range is acceptable. To enable infinity focus, a larger lens deformation is needed from the actuator. Future work will miniaturize the prototype and further reduce the driving voltage.

Figure 5 The tunable liquid lens, which is idle on top of a grid paper.

Figure 6. Demonstration of optical tuning using the DEA diaphragm pump

Table 1. Performance comparison among various designs of tunable liquid lens using DEA

	Carpi et al (2012)	Shian et al (2012)	This work
Actuator material	VHB 4905	VHB 4910	VHB 4910
Actuator Pre-stretch	4x4	2x2	Variable
Electrode material	Carbon grease	Single-walled carbon nanotube	Graphite powder with oil immersion
Lens diameter	7.6mm	-	8mm
Accommodation or tuning range	3cm to 10 cm	16cm to 770 cm	15cm to 50 cm
Driving voltage	Up to 4kV	Up to 5kV	Up to 1.8kV

5. CONCLUSION

We have reviewed the challenges faced by the DEAs for tuning liquid lens. The lens membrane with integrated DEA is subjected to high Maxwell stress and it is susceptible to the localized electrical breakdown. In turns, it may puncture, causing liquid leakage from the enclosure. This work we proposed a tunable liquid lens using a DEA diaphragm pump. By adopting complete dielectric-oil immersion, a DEA diaphragm could avoid pre-mature failures that frequently damages the DEA without oil immersion. Activation of the diaphragm pump could inflate or deflate the liquid lens by hydraulic pressure change. By separating the lens and actuator, the design allows more choice of lens membrane material, be it optical clear or more stretchable for large curvature change. In addition, it allows the electro-active elastomer be thinned downed and multiplied independently of the lens membrane. Future work will further the actuator and lens characterization and possibly miniaturize the design for further reducing the driving voltage.

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