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Improvement of Varioptic's liquid lens based on electrowetting: how to obtain a short response time and its application in the design of a high resolution iris biometric system

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ABSTRACT

This communication presents the results obtained for decreasing the response time of electrowetting-based real time focus correctors (liquid lenses). In order to provide a compact iris biometric system demonstrator, we have achieved a response time at 90% of 7.5 ms for a change in focalization from 0 diopter to 10 diopter with a liquid lens having an aperture of 1.9 mm. We have used a hydrodynamic fluid reorganization model to predict the features of these fast liquid lenses and evaluated the sensivity of the response time to the different conception parameters.

Keywords : liquid lens, response time, biometry, autofocus, electrowetting, electro-optical, iris, command law

1. INTRODUCTION

The security of materials, information and people is one of the great challenges the society has to face. To improve the security, one of the solutions considered is a fast development of biometric recognition: it would ensure the protection of owner's data or the identification of dangerous persons.

The two most efficient biometrics are the fingerprint and the iris biometry. Since the fingerprint biometry can be biased in the case of manual workers, whose fingers pattern are likely to be damaged due to their profession, the iris biometry is very likely to become the privileged biometric technology in the future. However, the development of iris biometry is for the moment limited, due to the difficulty to acquire a properly resolved image with a compact biometric device. It is commonly admitted that proper iris recognition needs 100 to 200 pixels in an iris diameter, meaning a resolution of 50 to 100 μm . [1,2]

The aim of the project IRISEM, supported by the French ANR, is to identify and mitigate the technical challenges for the development of compact, low cost, adaptive optics for the iris biometry. In this paper, we present why the project needed a fast, narrow angle, autofocus component and how such a component is achievable.

2. OPTICAL DESIGN OF THE DEVICE

The specifications of the device are:

- The object is expected in a volume of 10 cm (height) x 10 cm (width) x 1 cm (field depth). A first stage of optical tracking is used to place the acquisition volume at the good place.
- The acquisition is realized at 60 cm of the optical device.
- The image field targeted will have dimensions of 1,8 cm (vertical) x 2,4 cm (horizontal).
- The pixel size is 60 x 60 μm maximum on the eye.
- The size of the image is 1000 x 1000 pixel
- The exposure time is 100 ms
- A control loop is used to follow the micro-moves of the eye during the exposure time. The frequency of this control loop is 250 Hz
- A fast mirror is used to follow the eyes movements in x and y
- A fast autofocus liquid lens is used to target the image field.
- The image is obtained in the infra-red spectrum (between 700 and 900 nm), according to the ISO 19794-6 standard. For a good recognition performance, 250 pixels are required on the IRIS diameter.

Based on the specification of the iris image acquisition device, the specifications of the liquid lens are:

- Useful aperture : 2 mm
- Focalization range : -5 D / + 15 D
- Wave-front error (WFE) RMS on the useful aperture : 60 nm maximum
- Response time : 10 ms maximum
- Criteria for the response time: the change in focalization is at least 90% of the change required and the instant WFE RMS is less than the quasi-static WFE + 50 nm.
- The operating temperature is 20 ± 10 °C.

3. KEY PARAMETERS FOR THE SPEED OPTIMIZATION OF THE LIQUID LENS

The first step for the conception of a fast autofocus liquid lens is the determination of the parameters which could influence the response time. These parameters are listed in the following scheme (refer to [3] for more details).

Figure 1 : schematic view of a liquid lens

We chose to organize these parameters in three categories:

- Geometrical parameters (useful aperture, cone angle, height of each liquid phase)
- Physico-chemical parameters (density and viscosity of each liquid phase, interface tension between the two liquids, wetting forces between the liquids and the dielectric surface)
- Command law

In B. Berge precedent work on the liquid lens,[4] a hydrodynamic model has been defined in order to predict the response time of the liquid lens. In this ideal model (no friction between of the liquids on the dielectric surface when the focalization of the lens is changing), the response time of the liquid lens is determined by :

- The aperture of the liquid lens
- The viscosities of the liquids
- The dimensions of the cell
- The density of the liquids
- The interface tension between the two liquids.

A numerical simulation was used, and a good agreement was found between the experimental response time of the liquid lenses Baltic 617 and Arctic 316 and the predicted values.

When we simulated the response time of the liquid lens with the geometric parameters required for the iris biometry (useful aperture: 2 mm, thickness of the liquid layers: 0,6 mm each), we found the following results:

- In this geometry, the liquid's flow is not limited by the viscosity when it is in the range of the typical liquid lens liquids (conductive phase: viscosity lower than 5 cSt, oil phase: viscosity lower than 2.5 cSt).
- The speed of the liquid lens is highly dependent upon the interface tension between the two liquids.
- The speed of the liquid lens is highly dependent upon the useful aperture of the liquid lens.

Therefore we have chosen the following tunable parameters to optimize the response time of the liquid lens:

- Useful aperture of the lens
- Interface tension between the two liquids
- Optimization of the command law (in order to find the critical damping of the oscillating system)

Due to the non-ideality of the flow (some friction is expected when the liquids move on the dielectric surface), we have added two parameters:

- Surface energy of the dielectric material
- Inclination of the conic surface on which the liquids are moving. This parameter determines geometrically the contact angle range of the electrowetting phenomenon for a liquid lens focalizing between -5 to 15 diopter.

We have then studied experimentally the variation of the response time of the liquid lens when tuning these parameters.

4. VARIATION OF THE RESPONSE TIME TO THE USEFUL APERTURE OF THE LENS

We have first studied the relation between the response time of the lens and its mechanical aperture. For these experiments, a 1 kHz square voltage was applied to the liquid lenses. The voltage applied to the lenses was adjusted in order to change its optical power from 0 diopter to 1 diopter, 0 diopter to 4 diopters, or 0 diopter to 10 diopters. The voltage command is a single step. The optical power measurement is realized with a HASO Shack-Hartman wave front analyzer from Imagine Optic, France. The measurement is performed on a pupil with a diameter of 1.3 mm. The liquids used for this experiment are the liquids of the commercial lens Arctic 316, with an interface tension of 16.0 ± 0.2 mN/m at 20°C.

Mechanical aperture	RT for 0D to 1D	RT for 0D to 4D	RT for 0D to 10D
2.1 mm	136 ms	60 ms	24 ms
1.8 mm	105 ms	70 ms	30 ms
1.6 mm	95 ms	50 ms	25 ms

Table 1 : dependence of the response time to the useful aperture of the liquid lens

These results have shown a decrease of the response time with the decrease of the mechanical aperture for the small focus changes (1D or less), but the correlation between aperture and speed of the lens is less evident for larger focus steps.

5. VARIATION OF THE RESPONSE TIME WITH THE INTERFACE TENSION OF THE LIQUIDS

In second, we studied the relation between the response time of the lens and the interface tension of the liquids. The same 1kHz square voltage, adjustment of the voltage to the optical power required and single step command are used as previously.

The package of the liquid lens has a mechanical aperture of 2.7 mm and the measurements are made on a pupil of 2.6 mm.

Interface tension	RT for 0D to 1D	RT for 0D to 4D	RT for 0D to 10D
16 mN/m	134 ms	94 ms	58 ms
22 mN/m	80 ms	40 ms	16 ms
30 mN/m	18 ms	18 ms	9 ms

Table 2 : dependence of the response time to liquid/liquid interface tension

With these results, we see a strong variation of the response time with the surface tension between the oil and the conductive phase, in good agreement with the hydrodynamic model.

6. VARIATION OF THE RESPONSE TIME WITH THE CONE ANGLE

In third, we have studied the relation between the response time of the lens and the cone angle used for the design of the liquid lens. The same 1kHz square voltage, adjustment of the voltage to the optical power required and single step command are used as previously. The mechanical aperture of the lens is 2.1 mm, the measurements are made on a pupil of 1.3 mm and the interface tension between the two liquids is 16 mN/m.

Cône angle	RT for 0D to 1D	RT for 0D to 4D	RT for 0D to 10D
55°	136 ms	60 ms	24 ms
45°	255 ms	145 ms	125 ms
30°	620 ms	300 ms	130 ms

Table 3 : dependence of the response time to cone angle of the liquid lens

With these results, we see a very variation of the response time with the cone angle used for the design of the liquid lens. Our explanation is as follow: according to the literature, electrowetting hysteresis is related to friction of the liquids at the triple (oil, conductive phase, dielectric) interface.[5] Previous work of M. Maillard showed that electrowetting hysteresis is higher at lower contact angle.[6] A direct consequence of these two statements is: increasing the cone angle will increase the contact angle at 0 diopter, therefor it will decrease electrowetting hysteresis and friction. With a lower friction, the liquid lenses will be faster. This observation enforces the hypothesis of friction limiting the speed of the liquid lens.

7. VARIATION OF THE RESPONSE TIME WITH THE WETTING OF THE LIQUIDS

In fourth, we have studied the relation between the response time of the lens and the wetting of the liquids on the dielectric surface. The same 1kHz square voltage, adjustment of the voltage to the optical power required and single step command are used as previously. The mechanical aperture of the lens is 2.7 mm, the measurements are made on a pupil of 2.6 mm, the interface tension between the two liquids is 28 mN/m (same liquids for the two batches of liquid lenses), the cone angle is 45°. The same liquids were used for the two experiments, and the natural contact angle of the liquids on the surface is lower than 10°. The hysteresis is negligible for the two configurations, as expected from the contact angle value.[6]

Topcoat surface energy	RT for 0D to 1D	RT for 0D to 4D	RT for 0D to 10D
43 mN/m	45 ms	22.5 ms	10 ms
24 mN/m	32.5 ms	22.5 ms	10 ms

Table 4 : variation of the response time with the dielectric surface energy

In these results, the variation of the response time value with the surface energy of the coating is not very significant. However, the shape of the focus response as a function of the time may be very different, even when the calculated response time value is the same.

For example, the normalized responses curves for the step of 10 diopters are:

Figure 2 : normalized focus response as a function of time for two different surface energies. The focus variation is 10 diopter.

In conclusion, even if the measured response time between the batches of lenses is similar, the local slope of the response curve is higher when the surface energy of the dielectric is lower. It means the intrinsic speed of the device is higher for low surface energies.

We have not rigorously explained and modeled this effect, but we can explain this observation with an “adhesion” force between the liquid and the solid surface. When the surface has a low surface energy, the interactions between the liquids and the surface are minimum, there is no friction of the liquids on the surface. For higher surface energies, some friction appears between the liquids and the surface, making the response slower.

8. OPTIMIZATION OF THE COMMAND LAW

As exposed in B. Berge's paper,[4] the classical response of a liquid lens to a step command is a second order oscillator. We will consider the damping constant ε of this oscillator. Typically, the response time of the liquid lens Arctic 316 presented by Berge has $\varepsilon < 1$ (overdamped system). It is easy to accelerate this liquid lens by applying an overshoot of the step command. On the other side, for liquid lenses like the Baltic 617, the lenses maybe underdamped. This issue is particularly critical for the fast liquid lenses developed according to the preceding paragraphs, where we increased the stiffness of the liquid-liquid interface, the operating voltage of the step and decreased the friction between the liquids and the solid surface. Then, we needed a command law in order to accelerate underdamped systems.

Considering the following equation of a second order oscillator defined by the liquid lens :

$$1/\omega_0^2 \ddot{e} + 2\varepsilon/\omega_0 \dot{e} + e = v(t) \quad (1)$$

where ω_0 is the natural pulsation of the oscillator, ε is the damping factor, $v(t)$ the voltage applied to the liquid lens, $e(t)$ the optical power of the liquid lens.

We used the Laplace transform and converted this expression in:

$$(1 + 2\varepsilon p/\omega_0 + (p/\omega_0)^2)E(p) = V(p) \quad (2)$$

where $E(p)$ and $V(p)$ are, respectively, the Laplace transforms of the signals $v(t)$ and $e(t)$ with the variable p .

The transfer function $H(p) = E(p) / V(p)$ of this system is :

$$H(p) = 1/(1 + 2\varepsilon p/\omega_0 + (p/\omega_0)^2) \quad (3)$$

We then used a matlab simulation of this transfer function to analytically determine the stimulation producing the following response curve of the liquid lens:

Figure 3 : shape of the variation of the focus with time wanted

The result of this simulation issued the following shape for the optimal command law. The parameters of this command law are : $V1$, $V2$, and the slope. The values of V_i and V_f are determined by the electro-optical characteristics of the liquid lens.

Figure 4 : shape of the driving voltage used

When using the optimized command, the following results were obtained. The mechanical aperture of the lens is 2.0 mm, the measurements are made on a pupil of 1.9 mm, the interface tension between the two liquids is 31 mN/m, the cone angle is 55°. The step of focus is from 0D to 10D.

$(V_1 - V_i) / (V_f - V_i)$	$(V_2 - V_f) / (V_f - V_i)$	Slope (V/ms)	Response time (ms)
Command : single step			15
0.4	0	1.3	12.5
0.6	0	1.25	7.5
0.6	0	0.5	17.5

Table 5 : parameters of the driving voltage functions used. and the response time obtained. Sampling of the command : 1 ms. Sampling of the detection : 2.5 ms

This optimized command law proved effective for the optimization of the response time of the liquid lens.

9. CONCLUSION

In conclusion, we confirmed the dependence of the response time to the liquid-liquid interface tension predicted by Berge's model.[4] This model relies on "ideal" conditions where the friction phenomena are neglected. In his paper, Berge effectively established that some friction occurs and the damping measured is higher than the damping predicted for an ideal liquid lens.

We have proposed in this study a liquid lens design with an optimized response time of 7.5 ms at 90% for a change in focalization from 0 diopter to 10 diopter with an aperture of 1.9 mm. We have minimized the slowdown of the lens attributed to friction. The best design against friction is: a low surface energy dielectric (under 25 mN/m) and a cone angle of at least 55°.

Finally, when the critical damping is not achieved, we recommend a design of fast liquid lenses where the oscillating response is underdamped and we add the adequate damping with a specific command law.

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