Design of an all-liquid anamorphic imaging device

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Abstract. The design of a novel anamorphic optofluidic imaging system based on a pair of liquid lenses whose toroidal surfaces create different optical powers in the symmetry-axes is presented. Using electrowetting-on-dieletrics for actuation, a cylindrical fluidic system is actuated by 32 azimuthally-distributed electrodes allowing the definition of non-rotationally-symmetric surface shapes. We present the design and simulation of this optical system and show that an anamorphic ratio of 1.43 at a maximum field of view of 6.82° is attainable.

1 Introduction

Anamorphic optics have different optical powers in two orthogonal planes, allowing realization of optical systems with different magnifications and fields of view in these planes. Anamorphic lenses were most prominently used in cinematography where objectives composed of normal and cylindrical glass lenses enabled recording of widescreen scenes on standard film [1]. In addition to their historical purpose, anamorphic optics are also used in applications such as optical processors [2] and imaging spectrometers [3].

Anamorphic systems made of conventional glass lenses require many elements, making them bulky and their assembly complex. However, other ways of realizing them have emerged, using tunable devices such as liquid crystal displays [4] or fluidic membrane lenses [5].

Recent work on electrowetting-on-dielectrics (EWOD) tunable lenses with increased electrode numbers have shown the ability to produce surfaces with great shape variability, including double-plane symmetric surfaces [6, 7]. Based on these concepts, we demonstrate that a completely fluidic anamorphic system may be realized and propose a design for an anamorphic imaging device using two EWOD tunable liquid lenses within a single device.

2 Concept

The concept is based on a previously demonstrated technology that allows the integration of multiple liquid lenses inside a single cavity as well as a high degree of surface control through sectioned electrodes [7, 8]. By deliberately shaping the lenses to have different curvatures in two orthogonal planes, the resulting optical system has a different field of view in these directions.

Shaping of the liquid interface is enabled by a sectioned electrode area with 32 sections per lens. These electrodes are embedded in a polymer foil that is located on the inner surface of a glass cylinder as shown in Figure 1 (a). Two immiscible liquids of different refractive index are then stacked inside this cylinder to form two refractive surfaces which act as the lenses. A set of glass substrates with coated aperture structures seals the cavity and provides the required electrical connection of the lenses.

For an anamorphic lens, the desired surface shapes are toroidal and their control and voltage calculation is carried out as described in [7]. Figure 1 (b) shows a *Surface Evolver* [9] simulation of one of the final lens configurations that was done to verify their feasibility. A sketch of both active sections is given in Fig. 1 (c)(d), showing the intended difference in magnification. The XZ-plane is chosen to have a larger, the YZ-plane to have a smaller FOV. The ratio of both is called anamorphic ratio (AR).

The general design approach was to start with a paraxial description of the system to find starting values for a ray tracing simulation. An anamorphic imaging system can, in the paraxial case, be treated as two separate rotationallysymmetric systems bound by a common set of constraints [1]. These constraints are that the image and object planes have to coincide and that the lens positions must be the same for both systems. Additionally, some constraints arise from the liquid nature of the device such as the dependence of lens position on curvature due to volume conservation, or the limits on lens curvature due to the achie-



Figure 1. (a) Structure of the device, (b) double-plane symmetric interface simulated using *Surface Evolver* and (c)(d) simplified ray diagram of the two active planes (not to scale).

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vable contact angles. The first-order solution combined with fixed technological parameters such as the cylinder diameter of 5 mm was then used to do further optimization through simulation.

3 Simulation

For an anamorphic imaging system, there are three parameters that are of interest: anamorphic ratio, field of view and resolution. They are all relevant for optimization but there is a trade-off between them, such that a compromise solution must be chosen.

For optimization, raytracing simulations were carried out in *OpticStudio* where a model of all surfaces including substrates, liquids and the sensor, was implemented. To account for the position change when varying the lens curvature, a macro was incorporated that calculates the position as a function of curvature, linking the two variables. The lens surfaces are modelled as biconic surfaces with their conic constants set to zero.

Using this model, parameters such as lens volume, cavity length, curvatures, distances were optimized with regard to the previously mentioned design objective. Initially, an AR of 2.0 was targeted but had to be lowered to maintain image quality. As a consequence, the chosen values are a compromise that does not sacrifice too much of either AR, FOV or image quality (here RMS wavefront was used for optimization). The final parameters are a device length of 11 mm, object distance of 200 mm, an aperture diameter of 1 mm, a horizontal FOV of 6.82° and a vertical FOV of 4.77° leading to an AR of 1.43.

The imaging quality is evaluated using the simulated MTF, as shown in Fig. 2. Since the focal length and thus the NA are different for the active planes, the MTF has to be considered separately for tangential and sagittal planes. Due to the dependence in variables and the spherical nature of liquid interfaces, it was not possible to achieve diffraction-limited performance in both planes at



Figure 2. Simulated image-side MTF of the system with onaxis field and maximal field each in x and y. Fields are given in normalized field coordinates H(x, y).

the same time. Evaluating the MTF at the Rayleigh criterion yields an optical resolution in the image plane of 30.8 and 22.7 cy/mm for the x and y directions, respectively.

Finally, an image simulation was carried out to qualitatively judge the quality and demonstrate the anamorphic effect. Figure 3(a) shows the object and (b) the simulated image – the characteristic anamorphic compression along the x axis is clearly visible. Moreover, the difference in resolution along the axes can be identified by comparing the vertical and horizontal lines.



Figure 3. Image simulation of the system using *1951 USAF resolution test chart*: (a) imaged field of view for the given distances used as the source image and (b) the result of the image simulation exhibiting compression along the x-axis. Anamorphic data as given in the text.

In conclusion, we showed through fluidic and optical simulations the feasibility of creating an all-liquid anamorphic imaging device which has an AR of 1.43 at a maximum FOV of 6.82°.

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