3MPixels auto focus imager using liquid lens for mobile applications

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Abstract

A design of a lens module - including a liquid lens based auto focus - for 3MPixels 1/3" format sensors will be presented and critically analyzed. The design has been optimized for the state of the art liquid lens technology, associated with glass and aspheric plastic lenses, and for compactness requirement of the mobile phone application. Detailed optical simulations results will be presented in both object and image spaces.

The module optics exhibits an overall thickness of 6.6mm including the 3mm aperture liquid lens based on electrowetting, enabling a focusing range of 100mm-infinity with f# 2.8 and view angle 66°.

Experiments using commercially available fixed optics will also be reported and demonstrated. Advantages and limitations of this new auto-focus technology will be discussed, as well as future trends like MicroZoom concepts without moving parts.

Introduction

Several technologies of active lenses using liquids or liquid crystals have been developed. Some of them use deformable liquid chambers which are pressurized using external pumps [1-5]. Among these electrowetting actuated liquid lenses [7] have critical intrinsic advantages, combining large optical response as well as high optical quality.

Liquid lenses based on electrowetting are a uniquely good solution for miniature optical systems, like auto-focus or zooms for mobile imaging. When an optical lens has a diameter of a few millimeters, the electrowetting have basic advantages over other solutions to make active optic. MEMS technologies are especially suitable in the 10-120 µm size domain, but they are expensive, limited by the basic cost of processed silicon wafers. Also MEMS still have to prove their ability to overcome serious difficulties in packaging, resulting in reliability failures. On the contrary, for large size optical systems (diameters more than 15mm) the already established solutions in the camera industry have benefited from decades of development. Nevertheless these are motorized solutions where solid friction and ageing limits severely impact their use in mobile applications.

In this paper we present an optical design and experimental results demonstrating the possibility of making auto-focus camera using 3Mpixels CMOS or CCD sensors, in an ultra-compact overall size. The design associates a state of the art electrowetting liquid lens associated with 1 glass and 3 aspheric plastic lenses. The result is a 3Mpixel imager, f/2.8, 66° diagonal view angle, with overall excellent optical performances somewhat superior to the existing optics. In addition this will benefit of intrinsic advantages of the liquid lens technology (low power consumption, excellent reliability, fast response, easy integration).

The liquid lenses have been recently industrialized and qualified for mobile environment, which open the way to the kind of optical design we are presenting in this paper to become real systems.

Liquid lens Technology

The principle of an electrowetting liquid lens has been described by several groups in the recent past. Our particular realization is described in figure 1. Two liquids are embedded inside a transparent cell, these two liquids having the same density but different indices of refractions. One of the liquid is a conductor and the other is insulator. Electrowetting is used as a way to change the curvature radius of the liquid-liquid interface inside the liquid lens: a conical electrode is covered with an insulating layer. When voltage is applied between the conical electrode and the conducting liquid, the liquid-liquid interface glides along the conical surface while staying always centered on the optical axis [6].

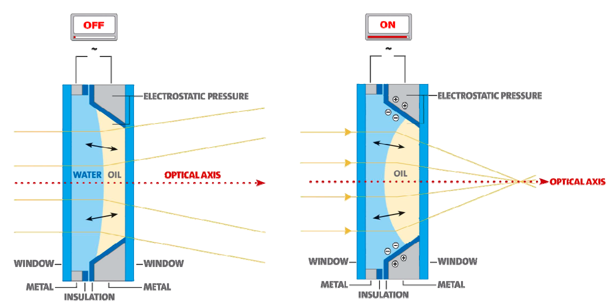

Figure 1: principle layout of the electrowetting liquid lens

The practical realization of this liquid lens has been made by Varioptic as ARCTIC 320 design, which incorporates a pair of liquids which have an index step of approximately 0,1. This design reveals quite good performances for the liquid lens, as shown on figure 2. Figure 2 shows the optical power introduced by the liquid-liquid interface as a function of the voltage. The optical power is defined as $\Delta n/R$, where Δn is the index step and R is the radius of curvature of the liquid-liquid interface. The optical power is equal to 1/f, where f is the effective focal length in the air, which is easily measured as the Arctic 320. One observes that the power range is quite large, of the order of 20 dioptries over 0-60V driving voltage.

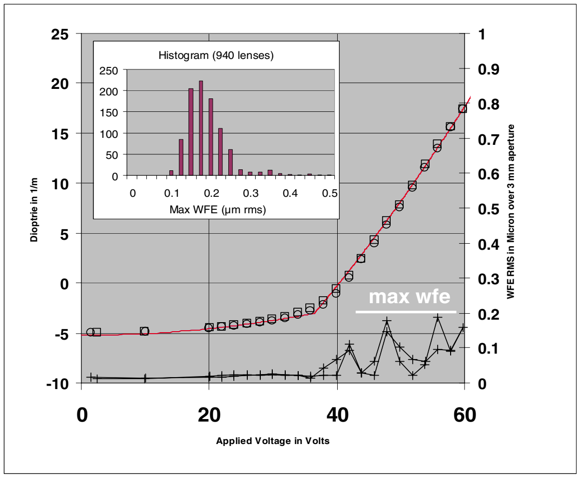

Figure 2: response curve of Arctic 320 lens, including WFE measurements with a best fit model(Line), Square are measurement data on a typical lens and + --- WFErms in micron. A typical distribution of WFE is also given.

The curve on figure 2 shows both upward and downward driving ramps, exhibiting almost no hysteresis. The optical quality of the lens is also shown on figure 2 as the wave front error (WFE rms) as a function of voltage. This curve also defines the maximum WFE for a given lens. The inset shows a typical histogram of the maximum WFE when a statistical batch of lenses is produced (90 lenses batch). This inset reveals a very good overall optical quality of lenses, maintained statistically.

Optical design

The design layout is given in figure 3, the design is highly compact, 6.6 mm from the front lens to the sensor plane.

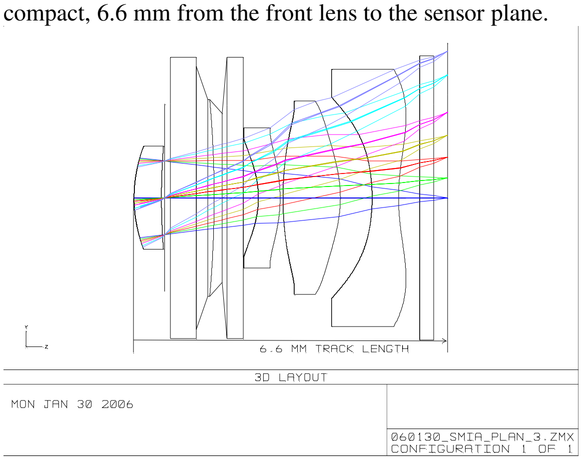

Figure 3. 3Mega pixel lens layaout

The non-telecentricity angle is smaller than 23 degree over the full FOV. The distortion is smaller than 3% and the field curvature over the full spectral range is smaller than +/- 70 microns as shown on figure 4.

The relative illumination is well over the common requirement for CMOS sensor and is given on figure 4.

The MTF at 80, 100,110 lp/mm are given curves for an object located at infinity is given on figure 5. The MTF curves for an object located at 120 mm from the sensor are given on figure 6.

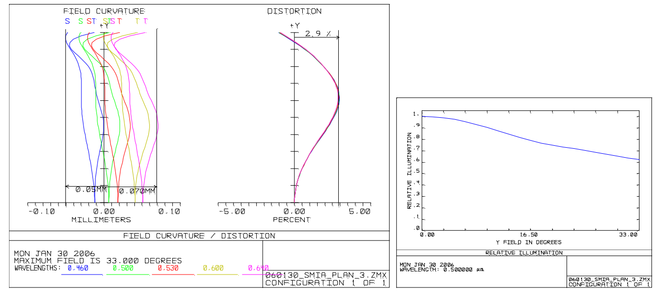

Figure 4. Field of curvature and distortion; Relative illumination

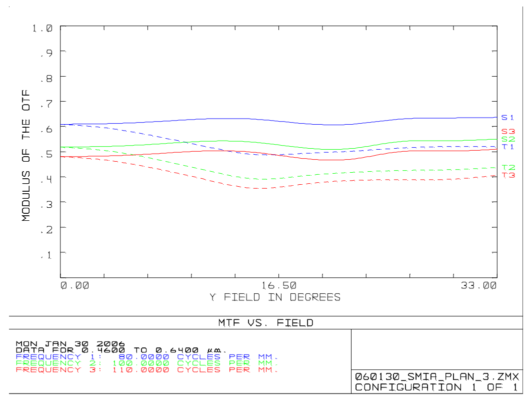

Figure 5. Polychromatic MTF , Object at infinity

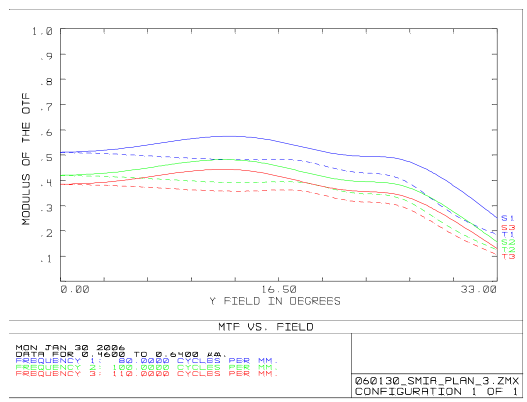

Figure 6 .Polychromatic MTF, object at 120 mm distance

Prototype description and results

The prototype that we demonstrated has been built up from a commercially available fixed optic from Sunex (USA) DSL 872 and a Varioptic lens Artic320 mounted on a 2 Mega pixels CMOS sensor. The Varioptic lens has been mounted on the Sunex lens front stop aperture.

The embodiment of the complete lens module has been designed by Sunex is sketched on figure 7. The lens has an effective focal length of 4.8mm, open at F/2.8, a diagonal field of view of 62deg.

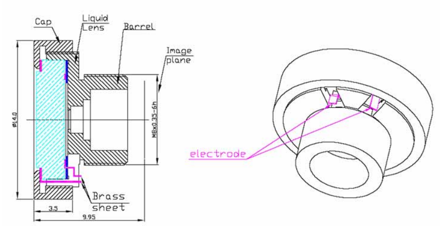

***Figure 7**. Mechanical overview of the prototype*

The expected MTF (@ 25, 50,75, 100 pl/mm) of the compltete lens module at different object distances of 400 and 200 mm are presented on figure 8 to Figure 9.

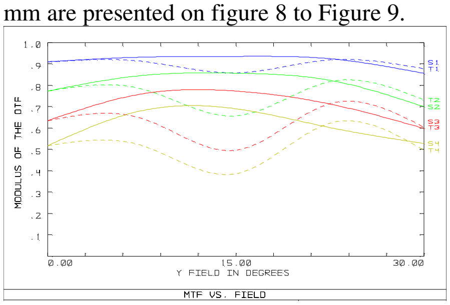

***Figure 8**. Polychromatic MTF at 400 mm object distance*

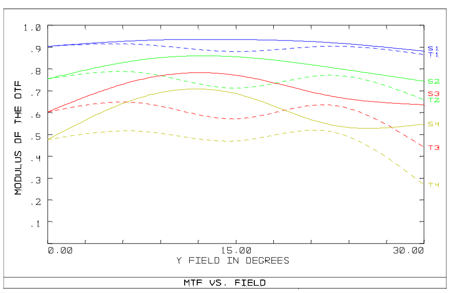

***Figure 9**. Polychromatic MTF at 200 mm object distance*

A picture of a flower located at about 100mm from the lens is shown in on figure 10 to demonstrate high image quality image obtained with this prototype.

Discussion

We demonstrated that the electrowetting technology can very easily and at low design cost enable a high quality fixed focus lens system in a valuable auto-focus system by simply adding the Varioptic lens on top the fixed lens.

Adding a liquid lens on top of a fixed lens system without re-optimizing of the complete system has some limitation (bulky assembly, not optimized optical quality). The compactness can be improved by placing the liquid lens in between fixed lens as presented in the theoretical design. Moreover the liquid lens, by changing its liquid interface curvature, is basically introducing a Petzval variation resulting in filed curvature at very close distance and some residual astigmatism.

This effect could be drastically reduced by well balancing the optical design optimization. Nevertheless this effect of field of curvature may not be so critical especially in the object space.

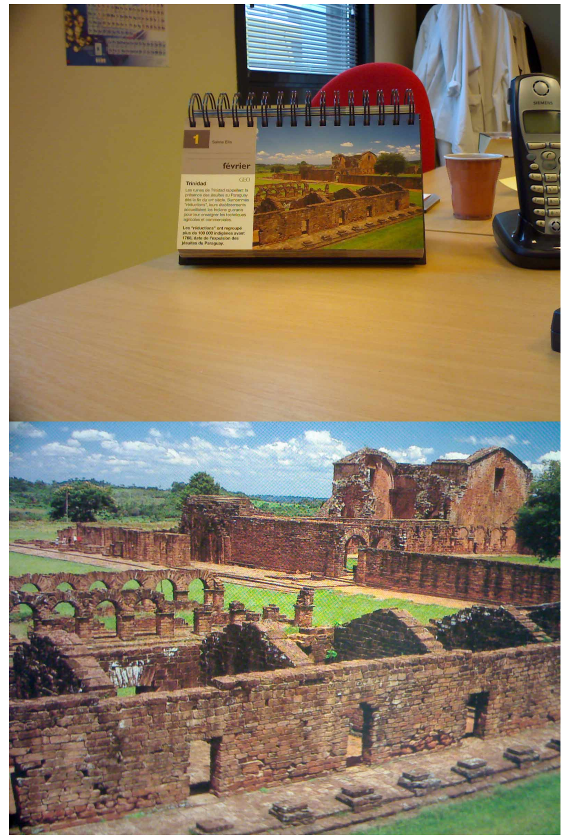

***Figure 10**. Picture at far distance and at 50 mm object distance taken the prototype.*

Common engineering practices in the imaging application push to match the lens system resolution to the sensor resolution. The lens performances are then usually specified at the sensor resolution limit. Nevertheless, this requirement does not need to be completely achieved on the full range of focus variation to insure a good image quality feeling.

When an object is moved closer to the imager system, its frequency content do not change, but the intrinsic resolution of the imager will increase as shown on figure 11.

All the simulation presented hereafter have been computed for a F/2.8, effective focal length of 4.6mm and a residual WFE of 0.15 lambda of the fixed lens, a 3 mega pixel resolution sensor (1/3 inch sensor format) and a minimum MTF limit of 30%. Those simulations are based on the formula (1) (reference [8]):

$$\mathrm{MTF}(\eta, \mathrm{WFE}) = 2/3.1415 \times (\mathrm{acos}(\eta) - \eta \times \mathrm{sqrt}((1 - \eta)^2)) \times (1 - (\mathrm{WFE}/0.18)^2 \times (1 - 4 \times (\eta - 0.5)^2) \quad (1)$$

Where: η is the normalized frequency, $=\upsilon/\upsilon_c$ where $\upsilon_c = 1/\lambda N$, always $0<\eta<1$; λ is the wavelength in mm; N is the F umber of the optical system FN = F/D; F is the effective focal length; D is the diameter of the exit pupil; WFErms is the WFErms of the sytem in waves.

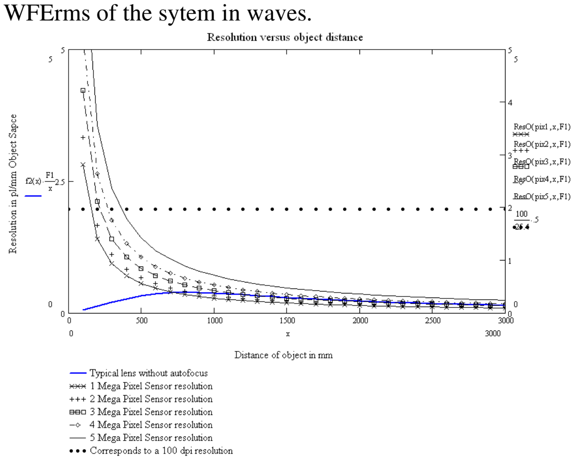

Figure 11. resolution in the object plane of fixed lens

From those curves we can see that without auto-focus the imager system will basically be limited by the sensor resolution from infinity to 500-1000 mm depending of the sensor resolution and without refocusing, it is basically impossible to have a better resolution than 100 dpi.

Obviously with a refocusing system this resolution can be achieved. With a liquid lens of a 10 to 15 dioptries range, taking into account the intrinsic actual optical quality of the liquid lens (~0.2 lambda on the useful aperture) figure 12 shows that the system is able to make an image with a resolution better than 100 dpi from a position of 100 mm to 200 mm range, and then make focus adjustment from 100 to infinity.

We think that the liquid lens technology can be used to enable auto-focus for imager system going up to a 5 mega pixel resolution if the intrinsic optical quality is improved from a WFE RMS of 0.2 lambda to a WFE RMS better than 0.1 lambda. The figure 13 gives the optical quality improvement roadmap.

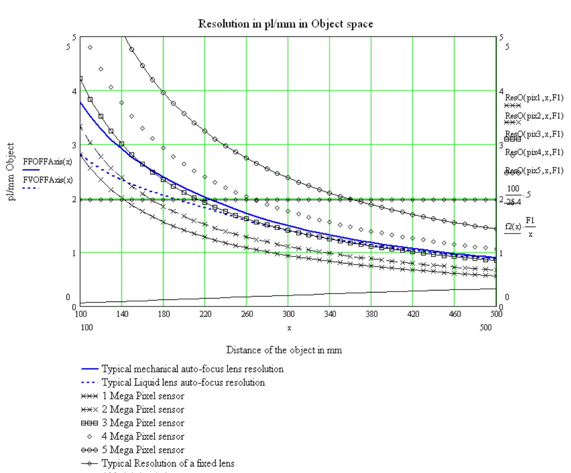

Figure 12. Resolution in the object plane using a liquid lens as the focus device.

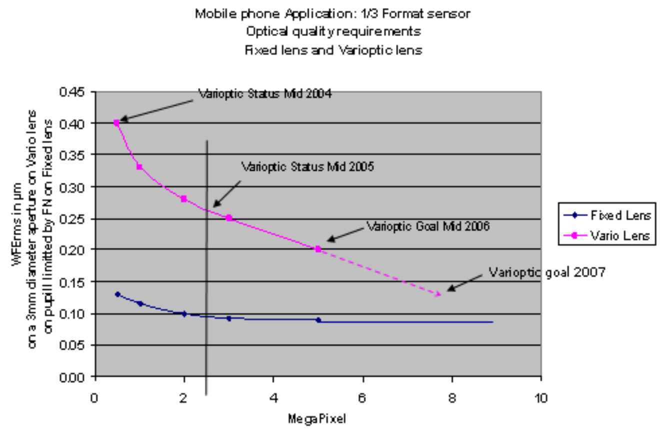

Figure 13 Optical quality road map

Conclusion

We demonstrated the feasibility of an ultra-compact, high quality refocusable lens system using liquid lens technology for a 3 Mega pixels sensor. This technology is particularly well adapted for imager in mobile application. Based on this analysis, we started to work on a micro zoom concept based on the electrowetting technology.

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Pierre Craen received his Master degree of physics from the University of Liege in 1990 (Belgium), his Master degree in Optical Engineering from "ESO, Paris-France" in 1993. Member of the SPIE, the author has been involved in Optical engineer R&D development since 1993 in different field of applications going from the development of optical instruments for space application (GOMOS) to industrial application (like laser Printing, & imager, barcode reading, projection,…). He has followed Varioptic development since 2001 and eventually joined the company in 2004.