Design of an autofocus lens for VGA ¼ " CCD and CMOS sensors

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ABSTRACT

We present the design of a lens for CCD or CMOS sensors using a new generation of lenses with electrically controlled focal length. These new elements made out of liquids (a drop of oil in water) work according to the principle of electro-wetting: the spreading of a drop of water on an electrically insulating surface can be modified by creating an accumulation of charges at the base of the drop. The densities of the two liquid phases are matched in order to keep the phases in place whatever the position of the lens.

This new lens can be used in small devices to achieve auto-focus camera modules. There are several ways to integrate our adaptive optic in a fixed camera module lens, classically made up of plastic lenses. We will discuss three different configurations for a VGA system with 4 mm focal length, f/3 aperture, 60° field. The optical resolution is excellent, for object distance going from 50 mm to infinity.

1. INTRODUCTION

Imaging systems or cameras generally need several adjustments of the lens system: focus adjustment and magnification. Since three decades, these adjustments have often been motorised for smooth and automatic control (autofocus). This situation has been well established in the camera industry, but appearance of miniature CCD or CMOS sensors (1/4" or less) has opened a different prospect. Applications such as web-cameras or camera modules embarked into mobile phones have pushed strongly the trend to develop miniature and cheap solutions. For these systems, which sizes are often of the order of 10x10x8 mm^3, conventional solutions for focus or zoom, based upon motorised movements, have been considered as too fragile and too expensive. The first generation of miniature camera modules has been constructed with CIF (352*288pixels) sensors and fixed optics. In order to maintain a reasonable depth of field, the lens was chosen with wide angle of view, and a high f#. With the increasing demand for optical quality in these applications, camera modules are currently developed with VGA (480x640 pixels) and Megapixel (1060*1280 pixels) sensors. These camera modules clearly need a focus adjustment system as the user might benefit from various applications with a broad range of object distance: family picture taking (1m-infinity), optical character recognition (30cm), 1D and 2D bar-code reading (20cm), personal identification based on fingerprint or pupil (10cm).

Current solutions to implement autofocus adjustments on a camera module are the following: (i) miniaturised motorised solutions, with the already mentioned drawbacks, (ii) other kind of electro-mechanical actuators, (iii) use of variable focal lens. Solutions (i) and (ii) have already been well documented, whereas the third is not.

Variable focal lens has been a long standing subject of research in many laboratories. In 1940, Graham [1] published a work on deformable membranes cells for manual variation. This basic principle has been thought to be interesting in other fields but seems difficult to implement in miniature optical systems as an external pump is required. More recently variable microlens arrays were developed using liquid crystal [2] but limited to lenses of very small size. Naumov and

collaborators [3] developed a variable focal lens made of a liquid-crystal slab actuated by external electrodes spontaneously producing a centro-symetric phase variation. Nevertheless, the focal length variation is very small (1-2 dioptries), clearly insufficient compared to the need (20 dioptries). Several companies have also published works on gel lenses whose optical power could be varied by an electrical current following into the gel [4,5]. To our knowledge, these solutions have never really been commercialised.
Since 1995, we have been developing a new type of lens: liquid lenses based on electrowetting [6], which provide very well for the need: variations of more than 20 dioptries, direct electric drive, good optical quality and self-centering mechanism. Two basic patents were taken and lenses are now developed for miniature and low-cost applications. We present in this paper optical design of lens for 1/4" imaging sensors, including a liquid lens for autofocus. These are example designs and this paper is not a comprehensive review of possible designs.

2. OPERATING PRINCIPLE OF VARIOPTIC'S VARIABLE FOCAL LENGTH LENS

We make small optical lenses with electrically controlled focal length, made out of two liquids of different index of refraction confined in a cell.
The operation of such lenses is based on the phenomenon of electrowetting ; the contact angle between a drop of water and an insulating surface can be monitored by changing the voltage applied between the liquid and another electrode (metallic substrate in figure 1).
In our lenses, a change in the value of this contact angle result in a variation of the curvature of the spherical oil/water dioptre. This is how we get a variation of the optical power of the device. The two liquids are formulated so their densities are as close as possible: this enables the use of the lens whatever the direction of the optical axis.
At 0V voltage, the dioptre is diverging; the power of the lens increases with the voltage.

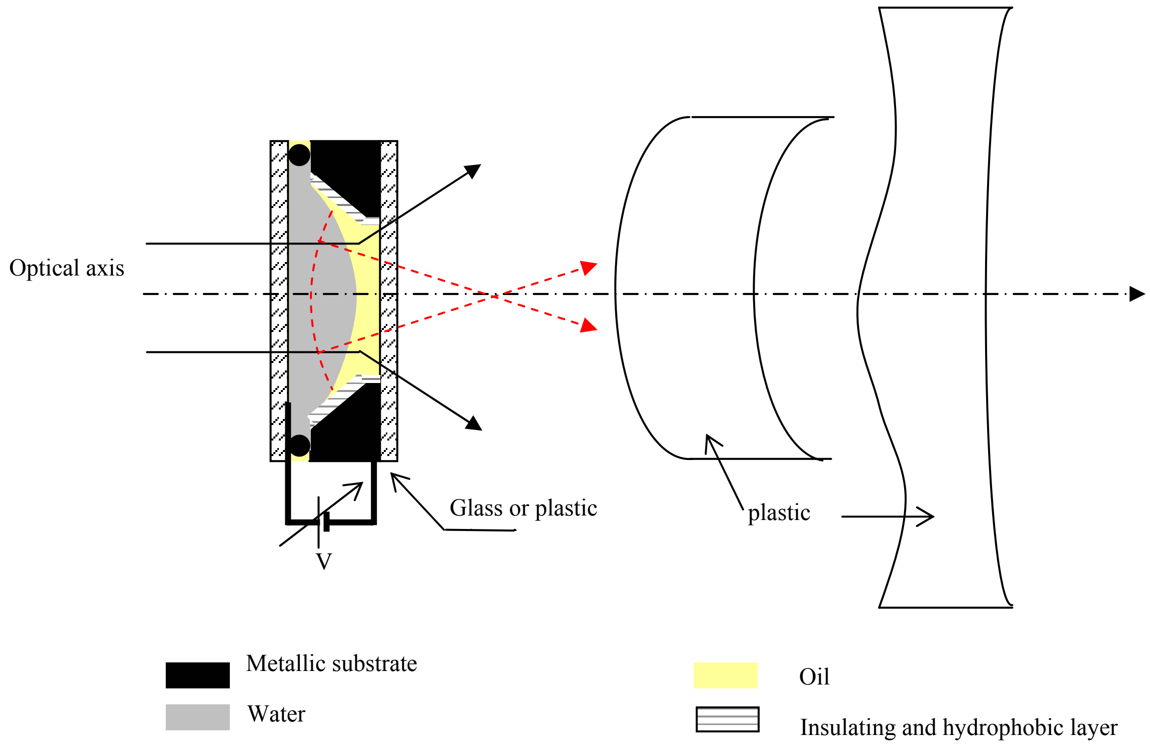


Figure 1 : side view of the variable focal length lens – example of integration into a fixed focus system

The power dynamics can reach 20 dioptries. For a lens aperture of about 4 mm, the focal length is roughly going from –5 up to 15 dioptries. As can be seen on figure 2, the phenomenon shows very little hysteresis. This graph shows the measured optical power of the lens versus voltage. For two different voltages (0 and 90 V), we also represent the shape of the defects of the wavefront transmitted by the variable lens. These images have been acquired using a Shack Hartmann wavefront analyser. They give a map of the residual defects of the wavefront, coded in colors: the wavefront is ideally spherical, but as the oil/water dioptre does not have a perfect spherical shape, it is distorted. These two images reveal the dependence of the optical quality on the applied voltage.

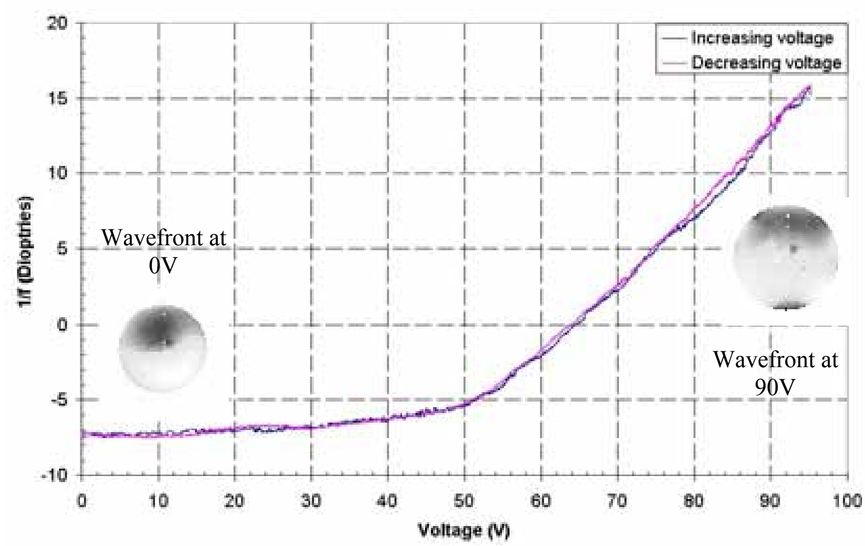
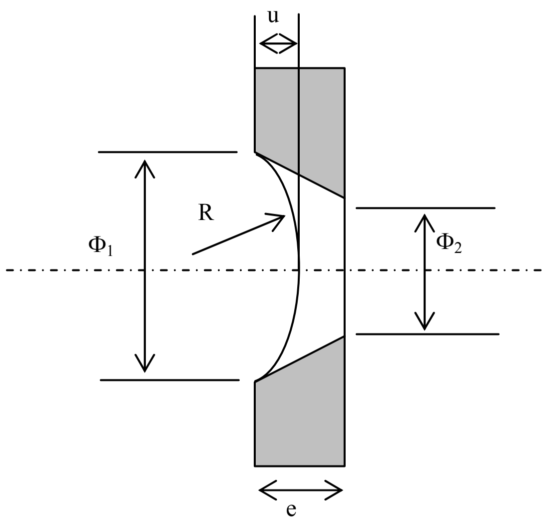


Figure 2: Optical power of a Varioptic lens versus voltage and transmitted wavefront

The focal length range directly depends on the geometrical dimensions of the lens. Thus, for given aperture Φ_1 and thickness e, the range of optical power is fixed (see figure 3). The table of figure 3 gives an example for the variations of R, the radius of the dioptre, and of u, the sag, versus voltage variation.



e = 0.75 mm
Φ_1 = 6 mm
Φ_2 = 4.5 mm

V/Vmax	R (mm)	u (mm)
0	-14.3	0.33
0.6	-40.8	0.24
0.8	14.5	0.06
1	5.7	-0.13

Figure 3: Variation of the geometrical characteristics of the lens versus voltage, for given aperture and thickness

With an optical component a few millimetres long, we can achieve sufficiently strong variation of the optical power to focus a camera module from an infinite to a 50 mm object distance.

Such properties make our device a quite suitable solution for integration in optical systems, especially auto-focus, in which a variation of focal length is required.

3. OPTICAL DESIGN FOR AN AUTOFOCUS FUNCTION IN VGA ¼" SENSOR CAMERA MODULE

We consider the integration of a variable focal length lens in a VGA ¼" sensor camera module. We simulated different designs for this integration.

The basic optical system is composed with two fixed plastic lenses; the first one ensures the convergence of the lens, the second one, strongly aspherical, corrects field aberrations. The image plane corresponds to the sensor surface. The sensor has 640*480 square pixels, the size of which is 5.6 µm. We set the total track of the optical system at a value of 4.8 mm. The optimisation of the optical system is calculated for different weighted half field angles from 0 up to 26° (or more) at 550 nm.

Three different designs are studied, designs A, B, C, with different position of the variable lens.

a. Design A:

In design A, the first still lens has been split into two parts that are used for embedding the liquids of the variable lens (see figure 4.a). The aperture of this design is f/3.65.
At first, the surfaces have been optimised in order to get the better quality of imaging for an infinite object distance, for all the field angle values.

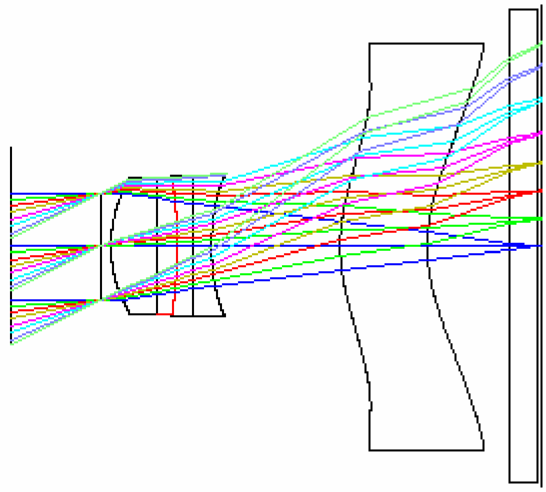


Figure 4.a : design A, 2D view of the optical system with ray tracing for 0°,4°,8°,12°,16°,20°,24°,26° half field angles.

Using Zemax software, we calculated the modulation transfer function (MTF) for different object distances going from infinity to 39 mm (see Figure 4.b). As we increase the voltage applied to the lens, we vary the radius of the oil/water diopter thus decreasing the object distance; for an infinite object distance, no voltage is applied to the variable lens.
For each of these object distance, at 80 cycles/mm, the MTF value is bigger than 50% for every field angle up to 20°.
The drop in the MTF becomes significant for field angles of 24° and 26° for object distances shorter than 58 mm.

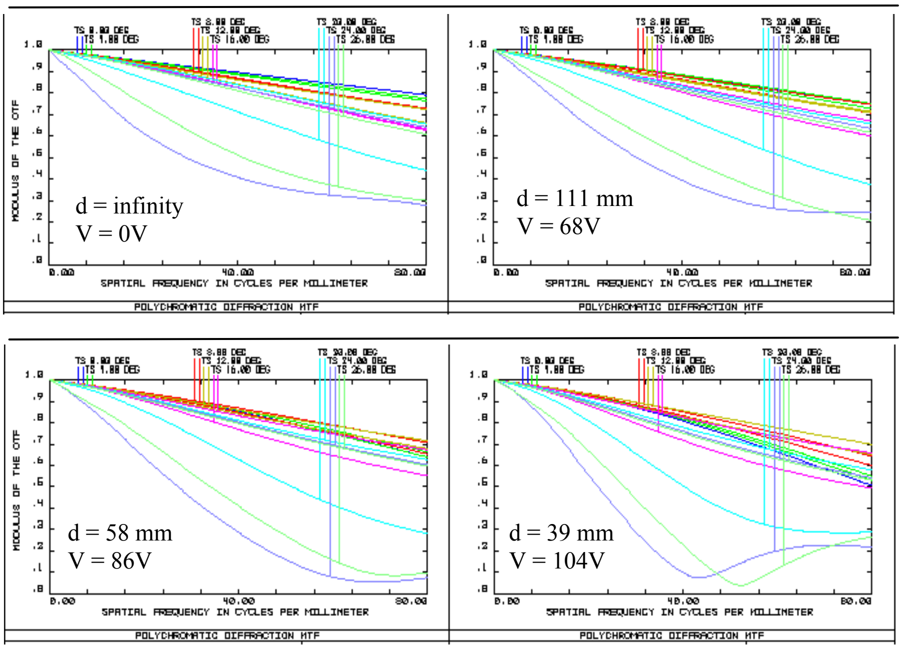


Figure 4.b : design A, MTF for different object distances (d) corresponding to different voltages (V)

We can get interesting information about the image quality on the sensor surface by calculating the ensquared energy at the image plane (Figure 4.c). It gives the percentage of total energy enclosed as a function of distance from the chief ray at the image of an object point.

This distance has to be compared with the size of a pixel (5.6 µm).

Here we can see that for field angles below 20°, more than 85% of the total energy is enclosed in a pixel.

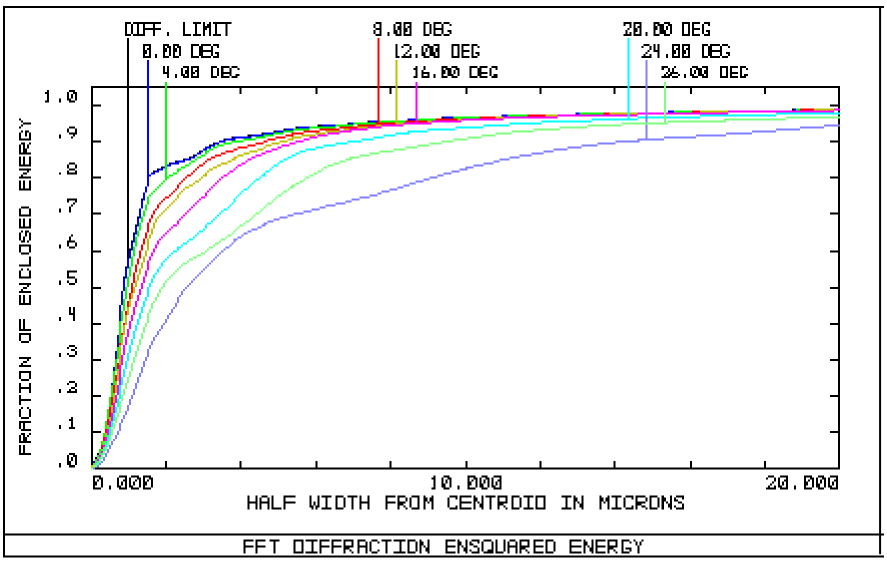


Figure 4.c : design A, ensquared energy

b. Design B

In design B, the variable lens is located between the two fixed ones (see figure 5.a). The aperture of this design is f/3.35.

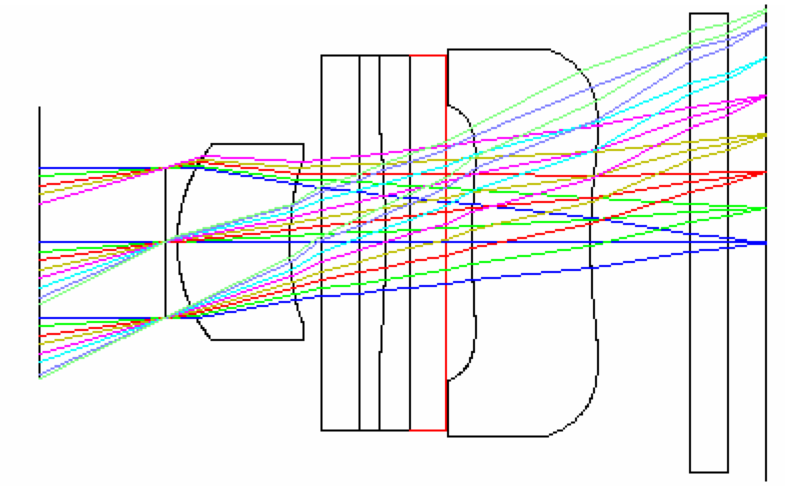


Figure 5.a : design B, 2D view of the optical system with ray tracing for 0°,4°,8°,12°,16°,20°,24°,26° field angles

The MTF is calculated for object distances going from infinity to 81 mm (see Figure 4.b)
On axis MTF is not as good as in design A. Though, the performances of the system in design B are also much less dependent on the object distance; we don’t have significant drop in MTF value for high field angles at close object distance.

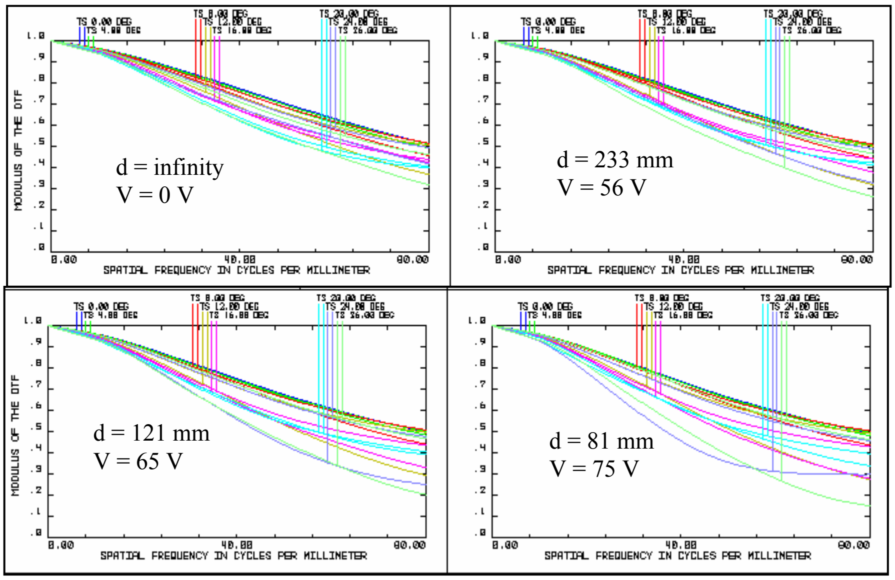


Figure 5.b : design B, MTF for different object distances (d), corresponding to different voltages (V).

On figure 5.c, we can see that for any field angle, more than 80% of the total energy is enclosed in a pixel.

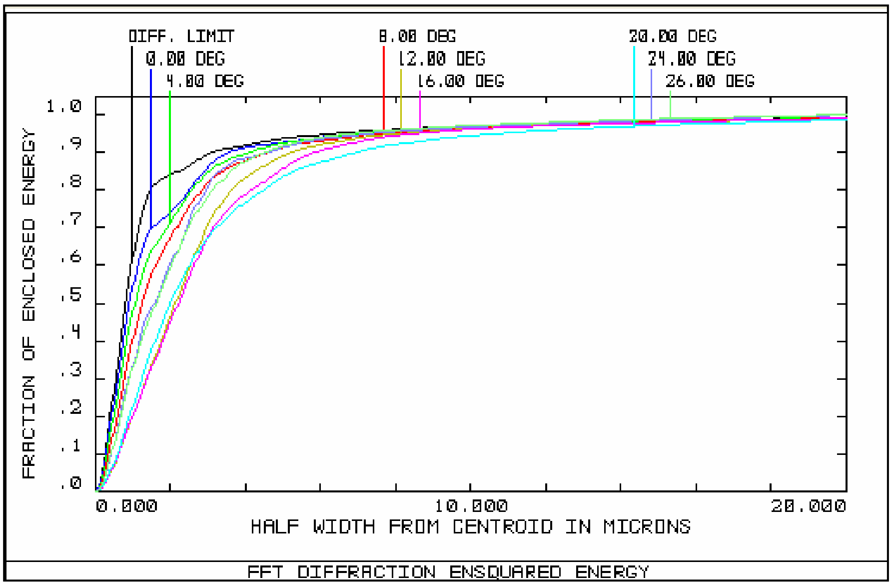


Figure 5.c : design B, ensquared energy

c. Design C

In design C, the variable lens is at the top of the system, which is here a perfect lens (without any aberration) with 4.8 mm focal length. The aperture of the system is f/2. The maximum half field angle is 33.5°.
We can see on figure 6 that, like in design B, we have a sharp decrease in FTM for high field angles at short object distances. There is no degradation of the optical quality at 0V.

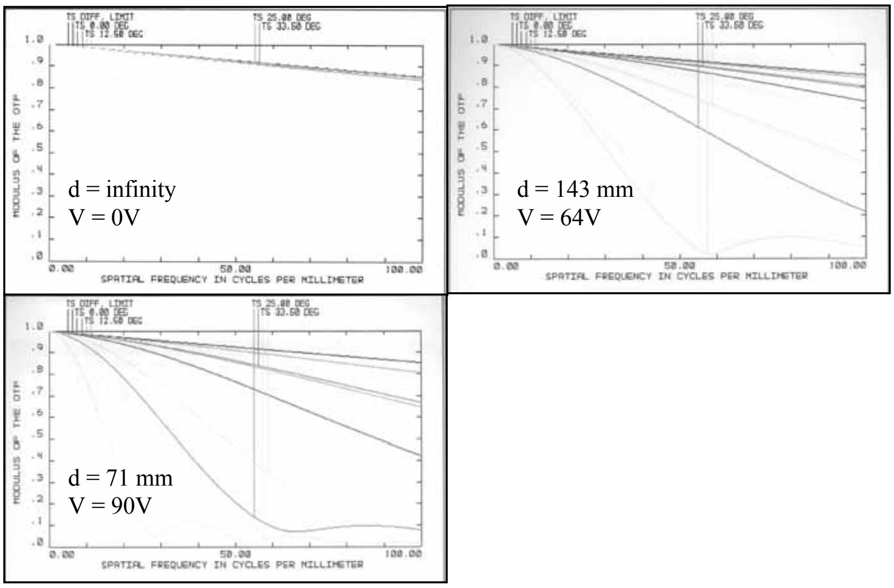


Figure 6 : Design C, headcapsule, FTM, at different voltages (V)

4. IMAGING BY DEMONSTRATORS INCLUDING A VARIABLE LENS AS A FOCUS DEVICE

We have assembled demonstrators for the variable lenses, so that we can easily evaluate by sight the optical quality of an optical system including the variable lens as a manual focus device. These demonstrators consist in a ¼” CCD sensor with a glass lens which efective focal length is 5.7 mm and aperture F/3.2 (Sunex, inc, DSL809). This lens is preceded by Varioptic’s variable lens.

Figures 7.a and 7.b show the pictures taken with such demonstrators with and without the variable lens, for infinite object distance. The picture of figure b was taken after refocusing the Sunex lens, in order to compensate the negative power of the variable lens at zero voltage. The qualities of these two pictures are quite comparable.

(a) (b)

Figure 7: Image for an infinite object distance by a demonstrator (a) without and (b) with variable lens

Pictures of an EIA resolution chart were taken with the demonstrator, with and without the variable lens, on axis and at full field angle (Figure 8). As for figure 7.a, the Sunex lens has been refocused before taking the picture with the variable lens on.
The optical resolution is about 400 lines on axis and 300 lines at full field angle, with and without the variable lens. This shows that using a variable lens does not decrease optical quality of the system.

(a) (b)

Figure 8: Image of an EIA resolution chart (1956), at full field angle, by a demonstrator (a) without and (b) with variable lens

5. CONCLUSION

Liquid lenses based on electrowetting appear to be good solutions as autofocus devices for ¼” electronic imaging systems: it has been shown in this paper that optical quality is excellent compared with current standards while having a very wide optical power variation, enabling focus from infinity to less than 50 mm.
Furthermore, such systems will benefit from low power consumption (a few mW) and fast response (20 ms) , which are specific advantages of electrowetting technology over most motorised solutions.

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